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RELIABILITY AND MAINTAINABILITY OF MECHANICAL SYSTEMS

BY

LIEUTENANT LOUIS K. BRAGAW, JR., U.S.C.G.

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

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AT THE

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MAY, 1964

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RELIABILITY AND MAINTAINABILITY OF MECHANICAL SYSTEMS

Louis K. Bragaw, Jr.

Submitted to the department of Naval Architecture and Marine Engineering and the Department of Mechanical Engineering on 22 May, 1964 in partial fulfillment of the requirements for the Master of Science degree in Mechanical Engineering and the Professional degree, Naval Engineer.

ABSTRACT

Money may be saved and reliability improved by the optimization of the scheduling of major overhaul of machinery systems. The techniques of Reliability Engineering and Operations Research are useful tools for this purpose. Successful analysis of one machine system should develop techniques for optimization of maintenance schedules for others.

In this thesis a Cummins VT 12M diesel engine is used, because of the large number of engines in service operation, and the data available. Information was gathered from shipboard machinery records of individual engines, from laboratory evaluation of the engine by the U.S. Navy Marine Engineering Laboratory, from the Naval Engineering Branch of the Third Coast Guard District, and from the Naval Engineering Division of U.S. Coast Guard Headquarters.

Reliability functions for selected components of the diesel engine, and for the most unaccessible diesel component group, are developed to illustrate a technique for evaluating the functions. The problem of optimum selection of a major overhaul schedule is pursued, by considering the reliability of the components of the most unaccessible group, upon which major overhaul is performed. The effect of reliability and maintenance management upon machine system total costs is discussed.

A problem in evaluating the reliability and maintainability of mechanical systems is the collection of data to evaluate reliability functions. An obstacle preventing earlier solution of the problem had been the lack of data. Reliability functions for individual components and machine systems are necessary to make reliability and maintainability theory applicable to mechanical systems.

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NOMENCLATURE

<u>Symbol</u>	<u>Meaning</u>
A	Activity, disintegrations/sec.
C_L	One sided lower confidence level
C.M.	Corrective Maintenance (C.M.) is failure repair, obviously scheduled only after the failure has occurred.
$E(t)$	Expected value, or first moment of density function
$f(t)$	Probability density function of failure
Fe	Iron
k	No. of life deviations corresponding to a reliability requirement
L	Two sided lower confidence level
M	Mean for the normal distribution
\hat{M}	Estimate of the mean for the normal distribution
M.O.	Major Overhaul (M.O.) is the most rigorous preventive maintenance that can be scheduled to refurbish, and, as far as possible, return a machine system to "as new" condition.
MTBF	Mean time between failure
m	Mean, for the exponential distribution
\hat{m}	Estimate of the mean for the exponential distribution
N	No. of target atoms in material being irradiated
N_f	Number of failures
N_o	Component population
No	Original No. of target atoms in material being irradiated

<u>Symbol</u>	<u>Meaning</u>
N_s	Number of successes
n	Number of components
n	Neutrons
P.M.	Preventive Maintenance (P.M.) is scheduled maintenance, short of a major overhaul
$Q(t)$	Failure distribution function
$R(t)$	Reliability function
$R(t)$ component	Reliability function for a component
$R(t)$ machine system	Reliability function for a machine system
r	Number of failures
r_w	Number of wearout failures
S_u	Measure of the standard deviations
s , or $\hat{\sigma}$	Estimate of the standard deviation
T	Total time
T_f	Expected or average time
t	Time
t_i	Life of component
t_{iw}	Wearout life of component
t_o	Interval between preventive maintenance
t_l	Given interval of time
$t_{l/2}$	Half-life
U	Two sided upper confidence level
$\overset{\circ}{W}$	Wear rate
X_e	Design clearance

<u>Symbol</u>	<u>Meaning</u>
α	(1- α) designates confidence level
α	Weibull scale parameter
β	Weibull slope parameter
δ	Weibull location parameter
γ	Gamma ray
Λ	Disintegration constant
λ	Constant instant failure rate
$\lambda(t)$	Instant failure rate, time dependent
σ	Standard deviation
σ	Material cross section, barns
$\sigma(M)$	Standard error
$\hat{\sigma}$, or S	Estimate of standard deviation
τ	Time
ϕ	Neutron flux of irradiation
χ^2	Chi-square statistical distribution

INTRODUCTION

Background

This is intended as a guide to the general development of Reliability Engineering and its application in Marine Engineering. The study of an existing marine system, to determine policies of operation, generally falls into the science of Operations Research.

Operations Research is the application of the scientific method to the study of existing physical processes and operations. It has been said that it is neither a method nor a technique, but a science defined by the combination of the phenomena it studies, its methods, and techniques. [1] Morse and Kimball [2] have said, "Operations Research is a Scientific Method for providing executive departments with a quantitative basis for decisions regarding operations under their control." Many descriptive works have been written describing the general field. [3,4,5,6].

Generally, an Operations Research problem falls into six major phases, covered descriptively in [4].

1. formulating the problem
2. constructing a mathematical model to represent the system under study
3. deriving a solution from the model
4. testing the model and the solution derived from it

5. establishing controls over the solution
6. putting the solution to work

No implication is intended that these steps are all applicable, conducted in this order, or for that matter, not recycled many times. It is desirable that there be a spirit of mutual interest existing between those intimate with a problem and the group conducting the work. [7]

Mechanical Reliability, and its effect upon Maintenance, has aspects that may be studied by Operations Research. [8] Reliability may be defined as the probability of survival, assuming survival also means acceptable function. As a probability, it must be expressed as a number, between zero and one. A widely accepted definition reads; "Reliability is the probability of a device performing its purpose adequately for the period of time intended under operating conditions encountered." [9] There are four key phrases in this definition of reliability, namely:

1. a probability
2. perform adequately
3. period of time
4. operating conditions encountered

The last phrase of the quotation, "... under operating conditions encountered...", is of utmost importance. To obtain a quantitative functional expression for reliability of a mechanical component, or machine, operating conditions under which the unit will serve must be defined. The definition must be

a model of actual service conditions. This enables laboratory development, evaluation, wear data, etc., conducted under the defined conditions, to apply. It also validates a post factum analysis of in-service failure reports.

Reliability Engineering has evolved in recent years from the general disciplines reviewed in [5] . It employs as tools both statistics and probability theory, to yield a statistical prediction of the nature, location, and frequency of component failure. Being a new subject, it is continuously developing and expanding, and much of the published work applies only to specific problems of limited use and interest. A discussion with references, on the organization and management of a Reliability Group, is presented in chapter one of [10] . The incentive for Reliability Engineering work is the resources that can be saved if reliability can be improved. This can be done through either, or both, design and preventive maintenance. Much work is being done to study and develop reliability applications for marine engineering. [11,12,13]

Data are necessary to make statistical studies and probability theory meaningful. [14,15] The laboratory testing of individual electronic components has been practical, and thus Reliability Engineering has advanced in the electronic field. [16] The collection of data in mechanical and marine fields has been more difficult for many reasons. [14,17,18,19,20,21]

Related to the collection of this data is the problem of the variation in stress level for mechanical components, in

apparently identical installations, both through variations in operation and environment. This problem is discussed in chapter 15 of [22] , and in [17] .

A pressing problem is the fact that mechanical components may have a failure rate interaction, that is, the failure rate of one in-service component is dependent on the condition of its interacting neighbors. [23]

For mechanical equipment, generally vulnerable to component wearout and other time increasing instant failure rates, the analysis of preventive maintenance versus system reliability may prove an economic necessity.

Reliability Data: Problem of the Machine System Manager

The machine system operator needs data on the performance of machinery systems, for several reasons:

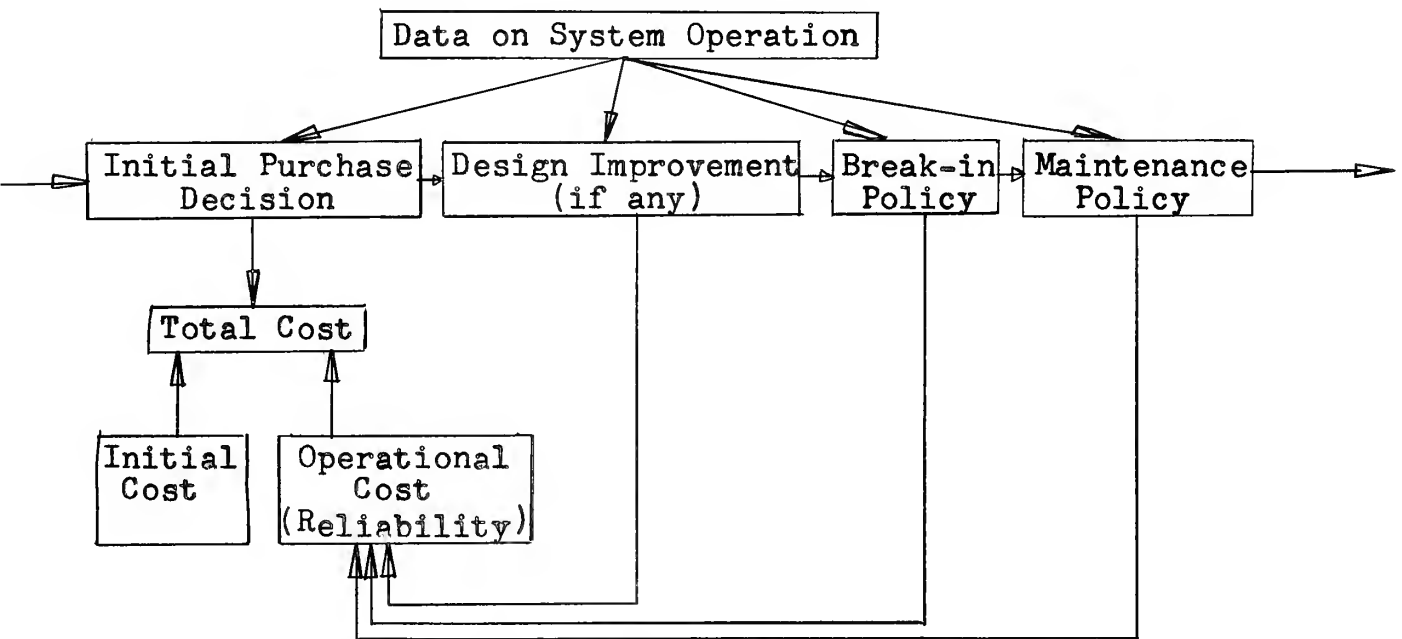
1. As an aid, along with initial cost figures, in making a decision on machine purchases.
2. To help improve the machine system purchased, by detecting the components with low reliability.
3. To develop a break-in policy. Here machines are run for a period to detect any abnormal components.
4. To determine preventive maintenance policies. The extent of maintenance operation may be limited by the accessibility of the components. For this reason we have various maintenance policies. The accessibility of components is important in weighing the cost of their renewal or repair.

In the discussion to this point, it has become obvious

that data on operation and failure are necessary to decide on design improvements, break-in, and maintenance policies. Figure I shows the flow chart for the introduction of a new system.

Figure I

Dollar Cost Feedback in the Development of a Machine System



From the chart we can see that the decisions on design improvement, break-in and maintenance policies affect the data which serve as feedback to operational cost. Operational costs, along with initial costs, are an integral part of the overall cost of the system, which of course is the economic measure for the decision in the first place to purchase the system.

Defining the Thesis Objective

Noting that data on operation and failures are important, from the time of purchase decision, through the period where maintenance policies are carried out, let us examine how we may

apply Reliability and Maintenance Theory to marine equipment, and thus contribute to the growth of the Theory.

We shall, in this thesis:

1. Explore a technique for determining reliability functions for individual mechanical components.
2. Explore a technique for determining the reliability function for a component group.
3. Determine the optimal major overhaul policy, and schedule, for a mechanical system, using the concept of determining the optimal overhaul policy, and schedule, of the least accessible group.

PROCEDURE

Purpose

The procedure lists the essential steps that are followed to obtain and evaluate the data that is necessary to determine individual component and component group reliability functions. The steps have been divided to perform the following uses:

1. Select a machine system for application of theory.
2. Discuss methods of data collection.
3. Define mechanical failure.
4. Discuss the necessary reliability mathematics.
5. Discuss the reliability of series and parallel systems.
6. Discuss the reliability distributions characteristic of various modes of failure.
7. Give a resume of data analysis techniques. Assign confidence levels to the data.
8. Develop the reliability function for an individual mechanical component.
9. Develop the reliability function for a mechanical system.
10. Determine major overhaul policy, and scheduling, for a mechanical system.

Selection of a Machine System for Application of Theory

Successful analysis of a mechanical component, or component groups, should develop a technique for operational analysis of others. Therefore the selection of a specific machine system should not limit the value of the research.

There are several considerations influencing the choice of a specific machine system. The population, number of machines in use, should be large, so that a large quantity of operation and failure records will be available. As it now appears that the next generation of Coast Guard cutters will have a form of diesel main propulsion, this machine system is of interest. The Coast Guard has an informative Material Failure Report, which is illustrated in Appendix A. The data from these reports may be used as a source of information on current engine performance.

A Cummins VT 12M diesel engine was selected for analysis in this thesis. There are four of these engines installed in each of thirty-five patrol boats, yielding a sample of one hundred and forty engines. Material Failure Reports for these engines have been reviewed at Coast Guard Headquarters, Washington, D.C. Data from evaluation tests of this engine at the U.S. Navy Marine Engineering Laboratory, Annapolis, Maryland, were used to supplement the in-service records.

Data Collection

Data on component and system operation and failure make reliability and maintainability of mechanical systems meaningful. Three sources of information on operation of the Cummins VT 12M turbo charged marine diesel engine have been consulted. They are:

1. Evaluation test of production prototype of the engine, by the U.S. Navy Marine Engineering Laboratory, Annapolis, Maryland.
2. Historical failure reports, filed at the Naval Engineering Division, U.S. Coast Guard Headquarters, Washington, D.C.

3. Historical failure reports, filed at the Naval Engineering Branch, Third Coast Guard District, New York, and aboard some of the patrol boats on which the engines were installed.

The evaluation tests of the prototype engine were conducted in 1960, a few years after the installation of similar units aboard the first of the thirty-five patrol boats of the ninety-five foot class. The engine evaluated was similar in all respects, and was tested at a power output of 600 bhp at 2100 rpm. The tests included a pretrial disassembly inspection, variable load and speed performance tests, cyclic life test, post-trial disassembly inspection, and tabulation of wear data. Wear data, in great detail, were recorded on pistons, piston rings, cylinder liners, sliding contact bearings, and crank journals. Measurements were taken using bore gauges, vernier micrometers, or feeler gauges, which ever was most applicable and accurate. For instance, cylinder liner wear was measured by bore gauge. All wear data were taken and recorded at several points sweeping out the wearing surface, and the points of maximum wear were used in the analysis in this thesis.

Failure reports for the main engines of the ninety-five foot patrol boats are all filed in one location in the Naval Engineering Division of the U.S. Coast Guard Headquarters. An electrostatic copy of each report on file was made, and then the reports were sorted into groups of related components. The report shown in Appendix A is designed to be submitted by

the unit experiencing the casualty to Headquarters by way of the District office.

The reports on file in the Naval Engineering Branch of one district were studied, and found to be identical to those in the central file. The machinery records of boats were examined and found to be similar. This is not proof that all casualties were reported by this form, but evidence that casualties reported to the district office, which controls repair funds, were forwarded to Headquarters.

To utilize these reports, an environmental block diagram is drawn, with an assumption that the 140 engines have, over their service use, been exposed to a uniform degree of operation.

If data were missing, because failure reports were not submitted, the estimates of reliability parameters would be too high, as they would be brought down by the number of failures, as discussed in data analysis techniques.

Definition of Mechanical Failure

How shall we define failure? A failure will be defined in this study as an inability of a component or machine to perform its designed function or output, when called into service. For example, we will define a failure to have occurred not only when a total, or catastrophic, breakdown happens, but also when out of tolerance wear occurs. Any event that requires the component or machine controller, human or automatic, to take a necessary system out of service, is a failure.

It is the nature of mechanical parts to go through a deterioration process, even though catastrophic failure may not occur. When a gradual failure progresses past a critical point, it sometimes interacts and causes failure in mating parts. This gradual deterioration of mechanical components makes a definite point of failure hard to define, and in most cases differs from failure experienced with electrical components. Similar problems exist in electronics when a component such as a resistor, capacitor, etc., drifts outside of tolerance. Several papers exist [24,24] discussing the mechanical failure phenomena, an event which seems only too familiar. They help define the point in mechanical degradation where a failure is considered to have occurred, short of total rupture.

Maintainability often appears with discussions of failure. It is defined rigorously as the probability that a failed system is restored to operable condition in a specified down time. Total down time includes logistic time, active corrective maintenance, or repair time, and administrative time. Recall that preventive maintenance and major overhaul do not count as downtime. Maintainability may be thought of as the ratio of the time a system is in operation, to the total time of operation and failure repair, C.M. [16] .

Reliability Mathematics

A mathematical definition and derivation of the reliability function have been developed, to fulfill the word definition

discussed on page 10. The reliability function, $R(t)$, is defined in the limit, as the population becomes infinite, as the ratio of the number of favorable events to the total number of events. This is the basic probabilistic definition.

$$R(t) = \lim_{N_0 \rightarrow \infty} \frac{N_s}{N_0} \quad (1)$$

The reliability of a limited number of components may be expressed as:

$$R(t) = \frac{N_s}{N_0} = \frac{N_s}{N_s + N_f} \quad (2)$$

where

$N_s \equiv$ Number of Successes

$N_f \equiv$ Number of Failures

$N_0 \equiv$ Component Population $= N_s + N_f$

From this basic definition a mathematical model for obtaining the reliability function may be obtained. [22] The development appears in Appendix B.

$$R(t) = \exp \left[- \int_0^t \lambda(t) dt \right] \quad (3)$$

The quantity $\lambda(t)$ is the instant failure rate, and in Appendix B is equated to $\frac{1}{N_s} \frac{dN_f}{dt}$. This is discussed further on page 23, and defined there by equation (11). Equation (3) describes $R(t)$ for any λ , whether $\lambda = \lambda(t)$ or a constant. Obviously, when

$\lambda = \text{constant}$

$$R(t) = e^{-\lambda t}$$

The distributive failure function $Q(t)$ which we will call the unreliability function, is defined as the ratio of failures to the total number of outcomes.

$$Q(t) \equiv \frac{N_f}{N_o} \quad (4)$$

Component failure and survival are complementary and mutually exclusive events. Failed components cannot survive, by definition. Thus

$$R(t) + Q(t) = 1 \quad (5)$$

The term $\frac{1}{N_o} \frac{dN_f}{dt}$, plotted against time, represents the number of failures per unit time, which is the failure density curve. Multiplication of $\frac{dN_f}{dt}$ by $\frac{1}{N_o}$ serves to normalize the

failure density curve, that is, impose the condition that it integrate to one over all time. We can see here that the reliability function is the probability distribution function of the failure density function [3], that is:

$$\text{failure density function} \equiv f(t) = - \frac{dR}{dt} \quad (6)$$

From the failure density curve we may obtain a first moment, sometimes referred to as the expected value or mean. In reliability studies it is called the mean time between failure, (MTBF) for repairable systems, and designated T_f . For nonrepairable

systems, the term mean time to failure is generally used.

$$E(t) = T_f = \int_0^{\infty} t \cdot f(t) dt \quad (7)$$

by (6)

$$T_f = \int_0^{\infty} R(t) dt \quad (8)$$

If we desire the mean time between failures, knowing that a system has operated successfully for a given period t_1 ,

then

$$R(t/t_1) = \frac{R(t)}{R(t_1)}$$

and

$$T_f = \int_{t_1}^{\infty} (t-t_1) \frac{R(t)}{R(t_1)} f(t_1) dt$$

where $(t - t_1)$ is the moment arm

so

$$T_f = \frac{1}{R(t_1)} \int_{t_1}^{\infty} R(t) dt$$

Now we develop the relationship between reliability and failure functions.

from (5)

$$\frac{dR(t)}{dt} + \frac{dQ(t)}{dt} = 0$$

from (6)

$$f(t) = \frac{dQ}{dt}$$

integrating

$$Q(t) = \int_0^t f(t) dt$$

$$\begin{aligned}
 \text{from (5)} \quad R(t) &= 1 - \int_0^t f(t) dt \\
 \text{or} \quad R(t) &= \int_t^{\infty} f(t) dt
 \end{aligned} \tag{9}$$

As stated on page 21, we must impose on it the condition that it always integrate to one, that:

$$\int_0^{\infty} f(t) dt = 1 \tag{10}$$

The instant failure rate, $\lambda(t)$, appearing in equation (3), is defined by the quotient of the failure density function and the reliability function.

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{11}$$

Reliability of Series and Parallel Systems

Chapters 10 and 11 of [22] outline the reliability of series and parallel systems, respectively.

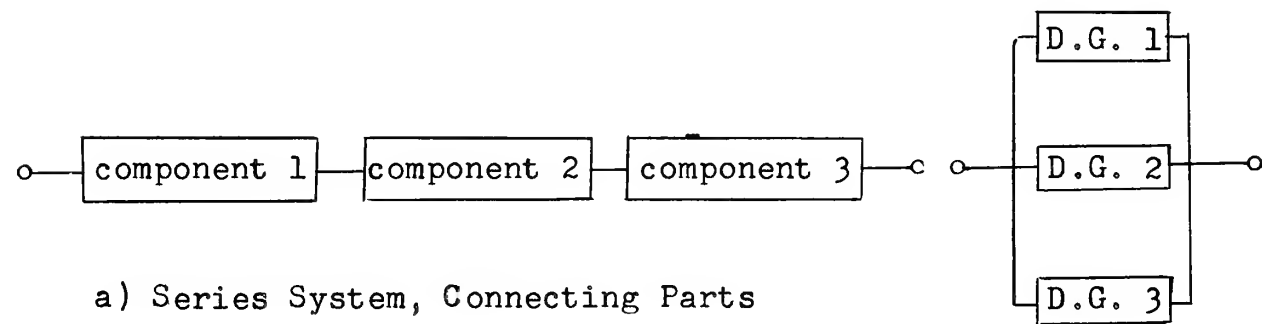
A series system of components exists when the components are so arranged that, if any fail, the system fails. The overall reliability of such a system is expressed as the product of the reliability of the individual components.

$$R(t)_{\text{series}} = R_1(t) \cdot R_2(t) \cdot \dots \cdot R_N(t) = \prod_{i=1}^N R_i(t) \tag{12}$$

As can be seen by Figure IIa, and equation (12), the reliability of such a system goes down by the magnitude of the reliability of each additional component.

Figure II

Flow Chart of a Series and a Parallel System



b) Parallel System, Diesel Generators

A parallel system of components exists when components are duplicated, so that if one fails, the duplicate may assume the duties of the failed component. The overall reliability of this system is expressed by the product law of unreliabilities in parallel operation:

$$R(t)_{\text{parallel}} = 1 - \prod_{i=1}^N Q_i(t) \quad (13)$$

If the systems in parallel are equal as is often the case, (3 engines, Figure IIb), this equation reduces to:

$$R(t)_{\text{parallel systems}} = 1 - (Q(t))^N = 1 - [1 - R(t)]^N \quad (14)$$

If the large assumption is made that one of the three smaller units, can, if operable, supply the demand, then for the 3 engine system pictured in Figure IIb,

$$R_{\text{parallel system}} = R^3 - 3R^2 + 3R \quad (15)$$

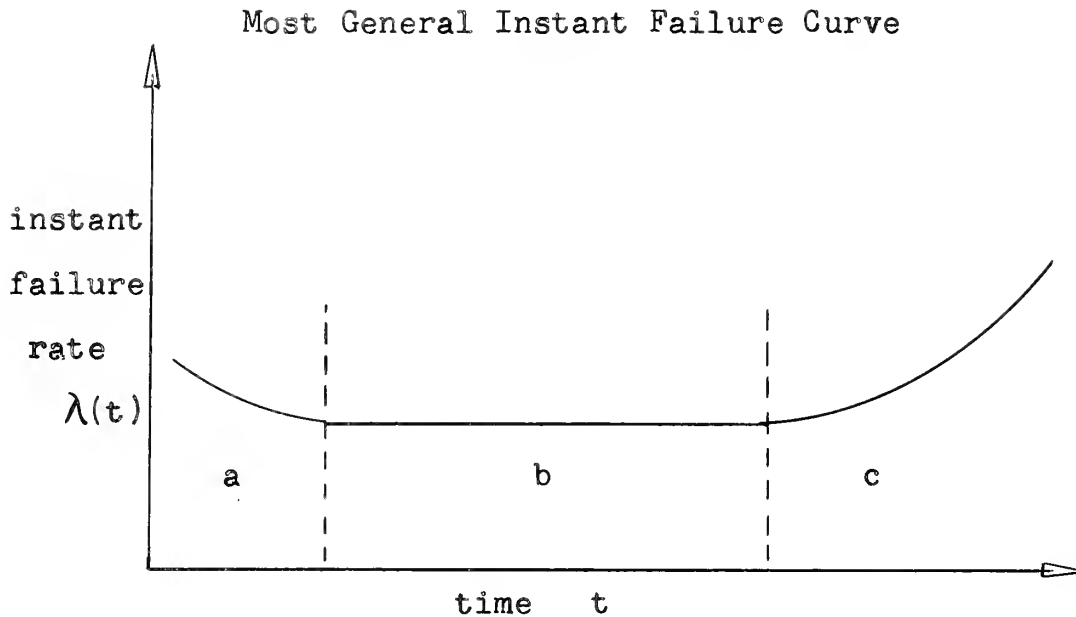
Thus, it is clear at this point that the evaluation of system reliability is possible only with precise determination of the component $R(t)$.

Reliability Distributions Characteristic of Various Modes of Failure

Each component possesses its own failure density function, which is related by equations (6) and (11) to the instant failure rate, $\lambda(t)$. The most general instant failure rate is the often quoted [7,22] bathtub curve, Figure III. It is divided into three parts. In the order of their appearance they are: [7]

1. initial failure, sometimes called debugging, burn-in
2. random failure period
3. wear-out period.

Figure III



For any machine system, an attempt is made to avoid period a, by break-in testing. There are standard periods when machinery is run before acceptance, or delivery, and again after maintenance. No attempt will be made here to examine what the length of this period should be.

Period b, random failure, and period c, wearout, have to be considered when examining the individual component. These periods are discussed on pages 27 and 28.

To describe mathematically the type of failure in any region of Figure III, let us review the major types of failure density functions, $f(t)$, as defined in equation (6). Reliability functions, $R(t)$, by equation (3), and instant failure rates, $\lambda(t)$, by equation (11), are related by equations (3) and (11).

These functions, together, may be represented by one of the following distributions: normal (or Gaussian), exponential, Weibull, gamma, rectangular, binomial, or Poisson. The functions and their plots are tabulated in this order, presenting $f(t)$, $R(t)$, and $\lambda(t)$ for each, in Appendix C.

To determine the reliability function for individual components, potential failure mechanisms must be considered. The failure mechanisms which the component could undergo may be categorized by examining data from conceptual design, development tests, and historical field reports. Each mechanism considered must be examined carefully to determine which type of failure distribution as described in the following paragraph applies.

A mechanism that occurs by chance, or human error, is by nature random, and thus represented by the exponential function. This distribution, as shown in Appendix C, is characterized by the mean (MTBF) or m , (in hours), or λ ($=\frac{1}{m}$), (components / hour). Note in Appendix C that the instant failure rate, $\lambda(t)$, for the exponential function is constant, that is, not time dependent. It is therefore understandable that chance events and human error would occur at a constant rate, that is, not dependent on time.

Wearout is represented by the normal distribution, as discussed in chapter 6 of [22]. It is characterized by a mean, M (in hours), and a standard deviation, σ (in hours). Fatigue

is represented by the normal distribution.

The Weibull distribution is a special function that, by adjustment of certain parameters, can be made to fit an exponential, normal, or any naturally occurring distribution. Note that the Weibull parameters may be adjusted to yield the bathtub curve of Figure II, and that the Weibull slope parameter, β , when equal to ten thirds will approximate the normal distribution. It has been found experimentally to be ten thirds for roller bearings, and three for ball bearings [26], and may represent the failure pattern of induction hardened cylinder bores, as stated in [27].

The exponential failure density function is sometimes used as a failure-probability model for a complex system. This is discussed in chapter 9.3 of [16]. The use of this function for a complex system is justified in that a myriad of forces may act upon the system and produce failure. Varying deterioration mechanisms, part failure rates, environmental conditions, all result in varied stress-strength combinations that produce failures randomly in time. If failures occur in this random order, they would have essentially a constant instant failure rate, $\lambda(t)$, characteristic of the exponential distribution.

Another justification would be to refer to the bathtub curve of Figure II. If break-in tests are successful, region a of the curve is avoided. It is entirely possible that the

period for which the assumption is made does not continue into region c, the wearout period. If this be true, then the instant failure rate, $\lambda(t)$, is constant. The assumption of an exponential failure density function is a good one, provided the system has not reached the period of wearout.

It has been shown that this is a good assumption on a system with no preventive maintenance [16] , or where preventive maintenance had not yet been performed. Preventive maintenance is performed on diesel engines, the system that will be used for example in this thesis. For a diesel engine, subsequent to preventive replacement of parts, a system with components of mixed ages results. The failure density function, equation (6) would be a composite effect. This was mentioned by Bazovsky [27] . However, the exponential function could be a good model for a diesel system, until the first preventive maintenance was performed, only if no wearout occurred. This does not seem a good assumption.

Resume of Data Analysis Techniques

To interpret data obtained for reliability evaluation, statistical techniques must be applied. Excellent surveys exist in [10,16] and chapter 22 of [22] . The methods differ for each density function outlined in Appendix C. These measurement and evaluation techniques differ also for constant population (replacement of failures) as opposed to variable population tests, for truncated (termination before the last failure) and non-truncated tests, and for a test truncated

immediately at the time of the last failure as opposed to termination at a later time, before occurrence of another failure.

The exponential function has as its characteristic parameter its mean ($m = \frac{1}{\lambda}$). The natural phenomena it represents were discussed on page 27. Referring to Appendix C for the function, we see:

$$R(t) = e^{-\lambda t} = e^{-t/m} = e^{-t/MTBF} \quad (16)$$

In service components are replaced as they fail, and their hours of operation are recorded. This suggests that the natural process is a replacement test, with termination, not necessarily at the time of last recorded failure. We must be careful when examining the failure reports to differentiate between wearout failure, and replacement for other reasons.

When the last failure occurs exactly at the point where the experiment is terminated, a point estimate, \hat{m} , of the mean, m , may be made [28] :

$$\hat{m} = \frac{nt}{r} = \frac{T}{r} \quad (17)$$

We designate the number of components by n , the number of failures by r , the time of the test by t , and the total component time logged in the test by T .

How much faith may be placed in the estimates of the true parameters? It is intuitive that statistical estimates are more likely to be near the true value as the sample size increases. An infinite sample alone would give full certainty or confidence that a measured parameter coincides with the full value. Confidence here means a mathematical probability relating the mutual position of the true value of a parameter and its estimate. Let us assume for a reasonable sized sample that the true value of the parameter will be somewhere in the neighborhood of the estimate, in a band, between two limits, determined by the "confidence" level specified.

Let us introduce α as the number specifying the confidence limit. A confidence level in percent is designated by $100 (1 - \alpha)$. A hypothetical example of "identical" gears, illustrated in Figure 36 of [17], well illustrates the effect of confidence levels. To determine confidence levels for \hat{m} , the chi-square distribution (tabulated on page 252 and 395 of [29]) of $2r$ degree of freedom is used [30] to show that the true mean, m , lies between an upper, U , and lower, L , limit, with a probability $(1 - \alpha)$. These limits are given by:

$$L = \frac{2r(\hat{m})}{\chi^2_{\alpha/2; 2r}} \quad (18)$$

$$U = \frac{2r(\hat{m})}{\chi^2_{1 - \alpha/2; 2r}} \quad (19)$$

If the last failure did not occur at the termination of the test, reference [30] shows that, for replacement or non-replacement, the so called two-sided confidence levels, are given by:

$$L = \frac{2r(m)}{\chi^2_{\alpha/2; 2r + 2}} \quad (20)$$

$$U = \frac{2r(m)}{\chi^2_{1 - \alpha/2; 2r}} \quad (21)$$

The problem can be varied to determine, with a probability of $(1 - \alpha)$, whether the true mean is equal to or larger than a certain value, usually referred to as the one-sided lower confidence limit, called C_L . For the exponential function, last failure not occurring at test termination,

$$C_L = \frac{2r(\hat{m})}{\chi^2_{\alpha; 2r + 2}} \quad (22)$$

This analysis will allow us to make estimates with probability of $(1 - \alpha)$ that the true mean, m , of the system lies between L and U , or that it is larger than C_L . We would also state that with a probability of $(1 - \frac{\alpha}{2})$ the true m is larger than L .

If no failures occurred during the test, we would not be

able to make a point estimate of m , but we would be able to obtain L and C_L , which should be of some value for indicating minimum requirements, and of evaluating the importance of a hypothetical mode of failure, as discussed on page 36. U and m clearly are infinite and of no value for the no failure case.

The normal reliability function has as its characteristic parameters the mean M , and the standard deviation, σ . The phenomena it represents were discussed on page 27. The normal function is listed with a plot in Appendix C, and the function representing wearout appears in Appendix D.

$$R(t) = \frac{1}{\sigma \sqrt{2\pi}} \int_r^\infty \exp \left[- \frac{(t-m)^2}{2\sigma^2} \right] dt \quad (23)$$

For a nontruncated test of wearout, the mean and standard deviation of a population may be estimated by:

$$\hat{M} = \frac{\sum_{i=1}^{r_w} t_{i_w}}{r_w} \quad (24)$$

$$\hat{\sigma} \equiv s = \sqrt{\frac{\sum_{i=1}^r (t_{i_w} - \hat{M})^2}{r_w}} \quad (25)$$

The denominator in equation (26) may be replaced by $(r_w + 1)$, instead of r_w , for a so-called optimum estimate of the standard

deviation.

When a normal distribution is being analyzed, the specific lives of several samples are distributed about the true mean of the population. It is intuitive then that \hat{M} obtained from n components, having experienced n failures, is distributed normally about the true mean life of the large population. The standard deviation of the mean is usually defined as the standard error, as discussed in chapter 8 of [31] , and designated $\sigma(M)$.

$$\sigma(M) = \frac{\sigma}{\sqrt{n}} \quad (26)$$

For analysis of our laboratory data, we will be interested in techniques for less than twenty-five samples. Here we must use the Student's distribution for $n - 1$ degrees of freedom, as tabulated on page 250 and 251 of [29] . Using the definitions and notation of one and two sided confidence levels, as given on page 31, we have:

$$L = \hat{M} - (t_{\alpha/2}; n-1) \frac{s}{\sqrt{n}} \quad (27)$$

$$U = \hat{M} + (t_{\alpha/2}; n-1) \frac{s}{\sqrt{n}} \quad (28)$$

$$C_L = \hat{M} - (t_{\alpha}; n-1) \frac{s}{\sqrt{n}} \quad (29)$$

As the normal distribution has a time increasing instant failure rate, overhaul intervals can be tied to the parameters and confidence levels already developed. Using t_o as time between scheduled overhauls, as on page 39, we could write an equation for t_o :

$$t_o = L - k\sigma \quad (30)$$

The term $k\sigma$ is the number of life deviations corresponding to a given reliability requirement. Where we cannot properly evaluate σ ($n < 25$) we have to replace σ in equation (30) by S_u , where S_u is defined by:

$$S_u = s \sqrt{\frac{n-1}{\chi^2_{1-\alpha; n-1}}} \quad (31)$$

Equation (31) becomes:

$$t_o = L - kS_u \quad (32)$$

This equation defines the time between overhauls, for the individual parts.

Development of a Reliability Function for a Component

To evaluate $R(t)$ of individual components, we depend on the definition of failure given on page 18, and the discussion of reliability functions for the individual failure modes, as given on pages 27 and 28.

When several mechanisms cause failure, $R(t)$ is equal to the product of the $R(t)$ of the individual mechanisms, as

stated by equation (12). This is so because, once failure with respect to one component has occurred, component failure, by definition, has occurred. The most common example of this is the $R(t)$ obtained from:

$$R(t)_{\text{component}} = R(t)_{\text{wearout}} R(t)_{\text{chance}} \quad (33)$$

which is pictured in Appendix D. This Appendix, in part c, also shows how the only $R(t)$ of importance, clearly, are those with the lowest m , or M , which is one of the most important aspects of Reliability Engineering. This fact cannot be over-emphasized. Even though data may never be exact, it quite often points out where small efforts will bring results, and where existing weakness is of no consequence because of the size of the weakness in comparison to others.

The reliability function for a component, $R(t)_{\text{component}}$, may be obtained by listing all events that could happen within reasonable limits of service experience. Each event should be examined to determine which type reliability function applies, and the parameters characteristic of the applicable function evaluated. Each function, once determined, should be multiplied by the product rule of reliability, to obtain the reliability function for the component, $R(t)_{\text{component}}$. For example, the product rule, equation (12) was used to obtain equation (16), page 30, assuming the mechanisms of failure were wearout and chance. Summarizing, the procedure for developing $R(t)_{\text{component}}$

is as follows:

1. List all mechanisms that could cause failure of the component.
2. Determine the function that would typify each mechanism.
3. Determine the most practical way of collecting data to determine characteristic parameters of each function.
4. Apply the product rule of reliability, by multiplying together the functions obtained for each failure mechanism. The product is $R(t)$ component.

Development of a Reliability Function for a Mechanical System

The function $R(t)$ individual component, when developed, will be valuable in an analytical method of obtaining $R(t)$ overall by combination of many $R(t)$ individual components, thus avoiding the exponential assumption. This method is known as interaction [23] , and requires a flow diagram of component interaction.

The mechanical system must be examined to delineate the basic component groups. The accessibility of the groups, as discussed later on pages 40 and 41 , must be considered in the division of the system into groups.

A flow chart of the interdependence of the components of a group is then drawn. The chart may be simplified by application of the rules of series and parallel systems. The function obtained, represents $R(t)$ overall, for the group or system analyzed.

Determination of Major Overhaul Policy and Scheduling

Before determining major overhaul policy, and, if necessary, scheduling, let us define rigorously the three types of maintenance.

1. Preventive Maintenance. Sometimes called "P.M.", preventive maintenance is scheduled maintenance, short of a major overhaul in scope. P.M. may be performed on a machine system in operation, or secured, dependent on the nature of the specified P.M. action, which may be overhaul of a readily accessible subgroup, or merely temperature or oil level, etc., inspections. Time required for P.M. does not count as an event unfavorable to adequate machine performance, that is, time for P.M. is not down time. There may be degrees of preventive maintenance. The degrees are defined by classifying the components of a complex system into groups, by the order of accessibility of each group. A j^{th} order P.M. would mean adjustment or a preventive renewal of some or all of the components of the j^{th} group.

2. Major Overhaul. "M.O." is the most rigorous preventive maintenance that can be scheduled to refurbish, and, as far as possible, return the machine system to an "as new" condition. Time required for M.O. does not count against reliability, i.e., against down time.

3. Corrective Maintenance. "C.M.", or failure repair, is the repair of a component, group of components, or an entire

system, that has failed in service, and is obviously scheduled only after the failure has occurred. "C.M." counts against reliability, i.e., for down time. P.M. and M.O. are scheduled to avoid all the losses associated with C.M.

Basically, there are three overhaul and corrective maintenance policies that can be followed [32] :

1. Perform no major overhaul, thus perform corrective maintenance as each failure occurs.

2. Perform major overhaul at specific intervals, regardless of intervening failures. This policy is dependent upon selection of the intervals, called t_0 . If a failure occurs during an interval, corrective maintenance is performed to repair the failure. An assumption is made that the repair does not affect the reliability function. The machine is returned to service and the original maintenance schedule is resumed. This is the system now in common use. The question arises as to whether this is an optimal policy, and if so, what are the proper periods for the specific engine.

3. Perform major overhaul at specific intervals determined by intervening failures. If there is a failure at t_i , then the next overhaul is to be scheduled at $t_i + t_0$. Here we assume the quality of corrective maintenance conducted at t_i return the system to its initial reliability. If this policy is optimal, the periods t_0 must be determined.

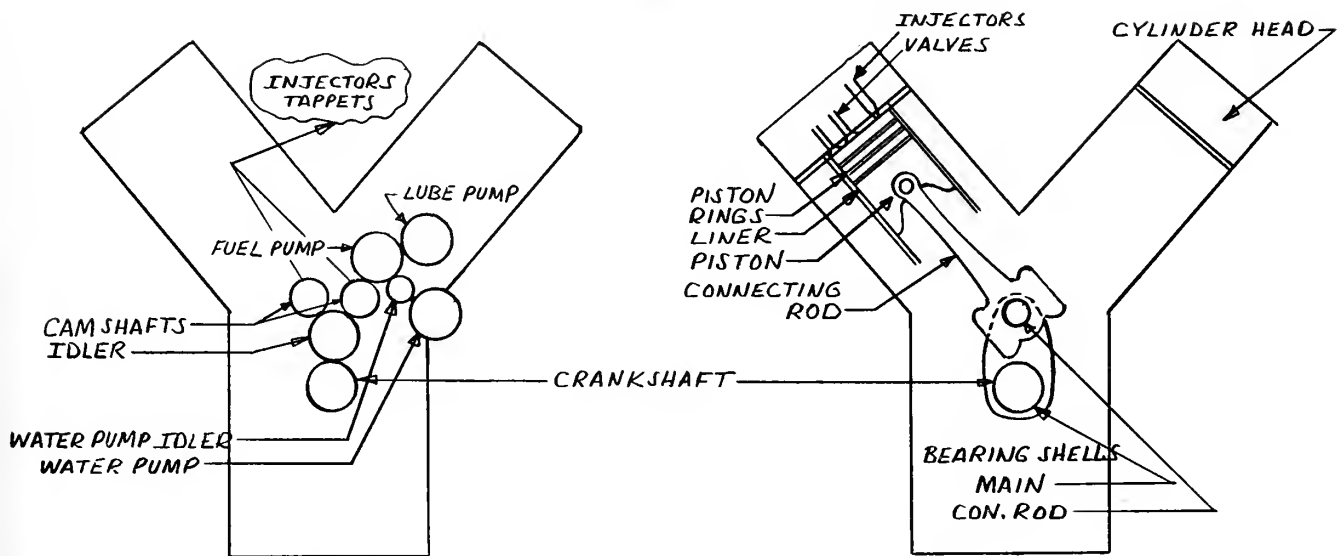
It has been proven by Drenick [33] that if the instant failure rate is constant (exponential distribution) or decreases with time, preventive maintenance is not beneficial. We know, because of wearout alone, that a mechanical component or system will have a constant, to time increasing, instant failure rate. Therefore we shall not consider policy one, and will examine further only policies two and three.

Accessibility of the components must be considered when considering policies two and three. Components and subsystems that can be maintained without major disassembly are items for preventive maintenance, rather than major overhaul. For the Cummins VT 12M the water pumps, fuel pump, lubrication pump, injectors, and tappets (see Figure IVa) fall into this category. If the cylinder heads are removed, in what is known as a "Top" overhaul, valve clearances, valve stems, rocker arms, piston crowns, upper walls of cylinder liners, and cylinder heads may be examined. Here the piston, piston ring, cylinder liner, connecting rod, bearing shells, and crankshaft are not available for inspection, and form a central group (see Figure IVb). Let us define disassembly and inspection of this group to be major overhaul.

The concept of accessibility in determination of major overhaul policies cannot be overemphasized because the scheduling of maintenance intervals is related to the accessibility of the components, and the service life of the faster wearing components, in the least accessible group. Some of the $R(t)$ component that

Figure IV

Cummins VT 12M Accessibility Diagram



a) end view, showing accessible components

b) end view, showing inaccessible components

will be developed, will be functions describing the faster wearing components of the central group. These functions will be employed, using the flow chart technique described in the "Development of $R(t)$ Machine System" section, to obtain $R(t)$ central group.

The central group function will be used to determine whether policy two or three applies. Statistical techniques, as employed to develop equation (33), will be used to determine t_0 of the optimal policy.

RESULTS

Reliability Functions for Individual Mechanical Components

The components making up the central group, as discussed on page 40 of the Procedure, were examined individually to determine their respective $R(t)$ component.

Development of Cylinder Liner Reliability Function

In an engine with cast iron cylinder liners, and chromium plated piston rings, the cylinder liners were found to have the higher failure rate [34]. For this reason, the VT 12M cylinder liner was the first component examined.

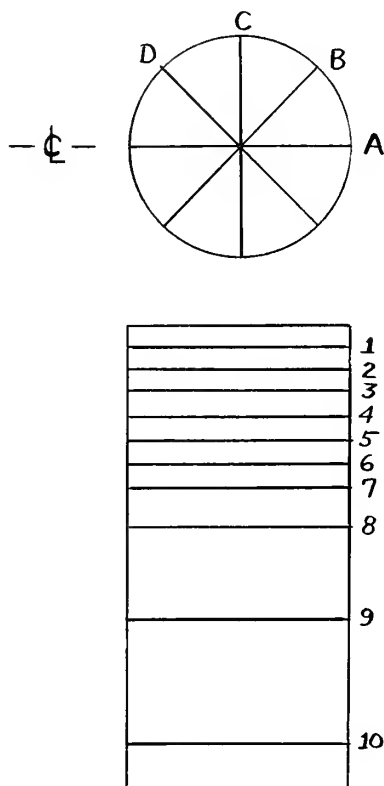
All Material Failure Reports for the cylinder liners were grouped and analyzed. The mechanisms of failure were found to be chance and wearout. A tabulation of in-service failures reported by Material Failure Report was made, and is presented in Appendix E, Summary of Data and Calculations, Table I. Fourteen failures were recorded prior to the first major overhaul. A mean, \hat{m} , for the exponential function representing these in-service failures was tabulated there, in Table IIA. A lower limit, L , at 90% confidence, was calculated in Table IIB, and will be used to represent a conservative estimate of the mean, \hat{m} , for the chance failure distribution.

Wear data were obtained from the cyclic endurance test, conducted at the U.S. Navy Marine Engineering Laboratory, Annapolis, Maryland. This test was severe, as can be seen by

inspection of the test schedule, in Appendix F. Wear measurements were taken at numerous stations along the cylinder liner, as shown in Figure V.

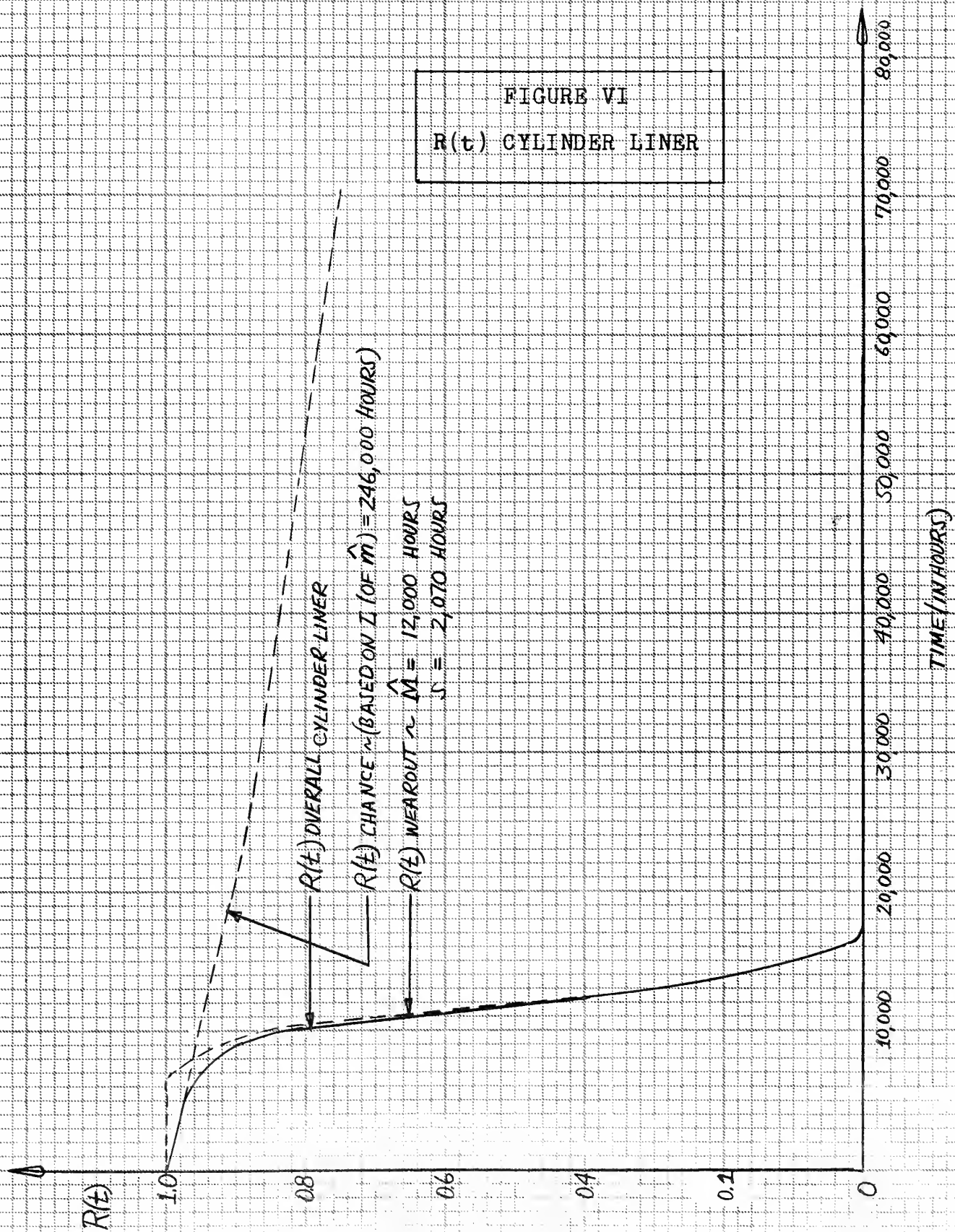
Figure V

Location of Wear Measurements
Cummins VT 12M Cylinder Liner



The location of maximum wear, without exception, was at the top of piston ring travel, as was discussed in [35, 36, 37], and data taken at this location were taken to compute the wear

FIGURE VI
 $R(t)$ CYLINDER LINER



rate. The assumption was made that this rate was constant over cylinder liner life [36, 37]. Next the life, t , for each cylinder liner, was computed, using the liner wear rate, W . The results were tabulated in Appendix E, Table III. A mean, \hat{M} , and standard deviation, $\hat{\sigma}$, were computed in Table IVB for the cyclic endurance tests, and in Table IVC for in-service wear measurements. The in-service wear measurements were taken on two engines during a major overhaul, performed after 3,000 hours of operation. Note that the in-service mean is four times greater than the Laboratory. The in-service ratio of standard deviation to mean is two and a half.

Thus the parameters \hat{M} , s , and \hat{m} have been identified, and the respective L 's determined, at 90% confidence levels. Equation (33) was used to obtain $R(t)$ cylinder liner. The plot of this function appears in Figure VI.

Development of Piston Compression Ring Reliability Function

Available reliability data for the piston compression rings were analyzed. The mechanisms of failure were found to be breakage and wear.

Examination of the material failure reports revealed that only twice had broken rings been found at a time apart from major overhaul. A tabulation of these in-service failures is presented in Appendix E, Summary of Data and Calculations, Table V. A mean, \hat{m} , for these failures (they appeared random), and a lower limit, L , at 90% confidence, as a conservative

estimate of m , was tabulated in Appendix E, Table VI.

Wear measurements, taken at the ring butt gap, were recorded during the cyclic endurance test. These data are presented in Appendix E, Table VII. Table VIIIA lists the sample calculations for wear rate, and ring life, and Table VIIIB calculates the parameters \hat{M} and s for ring wear.

The piston ring is the most inexpensive part in the central group. Whenever the group was disassembled in service, new rings were installed. For this reason it was hard to obtain wear data for the rings. Wear on the chrome plated rings was considerably less than on the iron liner, as evidenced in the cyclic endurance tests. We shall assume the service M to be four times greater than that resulting from the laboratory endurance tests. This is the ratio of in-service wear to laboratory wear found true for the cylinder liner. Take the in-service standard deviation, s , to be the same. Thus the in-service parameters for the compression ring are:

$$\hat{M} = 52,800 \text{ hours}$$

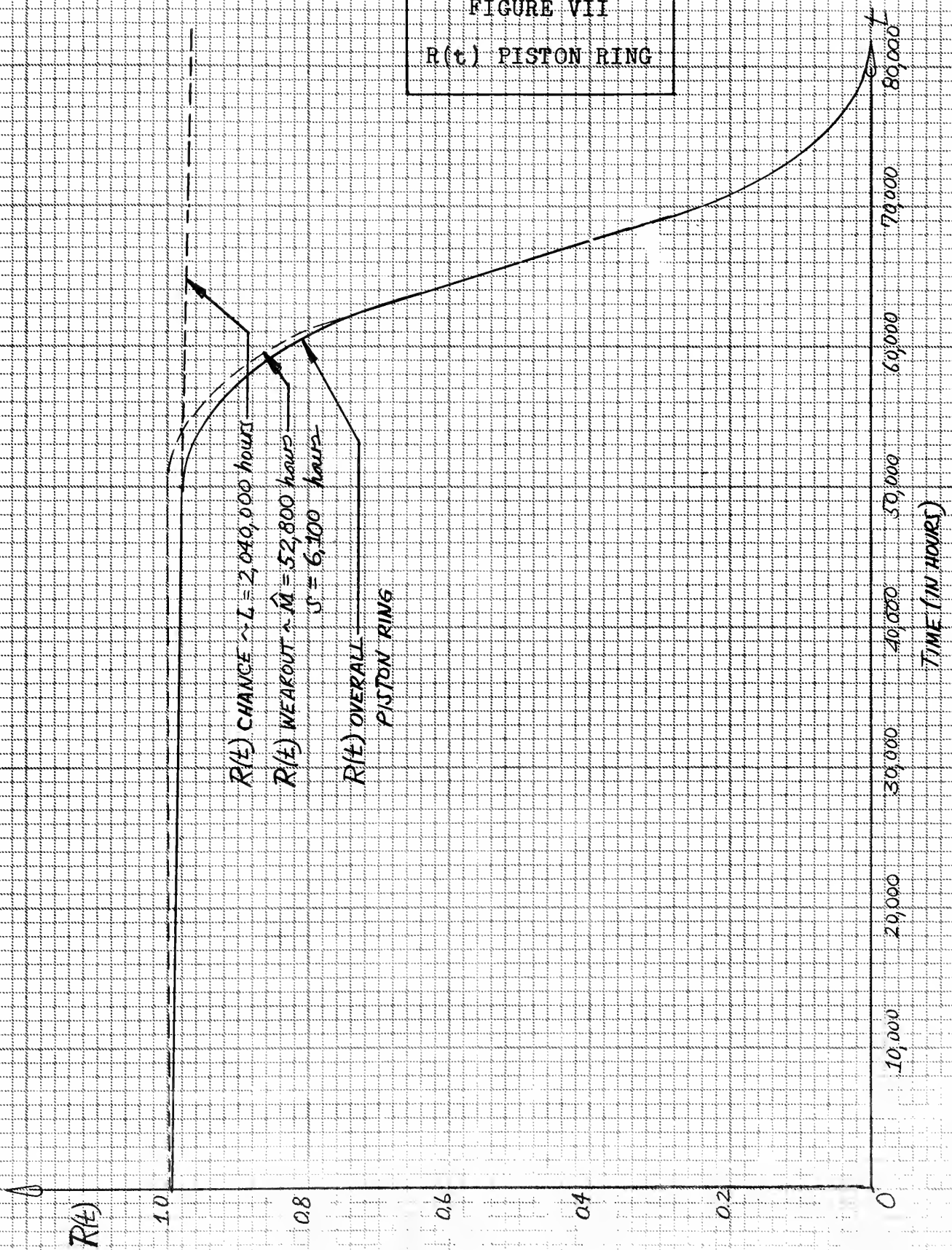
$$s = 6,100 \text{ hours}$$

The plot of $R(t)$ for the compression ring appears in Figure VII.

Physically the rings serve three purposes:

1. They seal the space between the piston and the liner, thus preventing the high pressure combustion gases, or the air charge during the compression stroke, from escaping down the liner.

FIGURE VII
R(t) PISTON RING



2. They transmit heat from the piston to the water cooled cylinder liner.

3. They damp out part of the fluctuations of the piston side thrust.

In the sense of the first listed purpose, three compression rings would constitute parallel system, as discussed on page 24 . Applying equations (13) and (14) and designating $R(t)$ for a single compression ring by R , then:

$$R(t)_{\text{compression ring system}} = 3R(1 - R + \frac{R^2}{3}) \quad (34)$$

The plot of the reliability function representing this system appears in Figure VIII. Comparison of Figure VII and VIII shows the reliability added through the parallel system.

Development of the Main Bearing Reliability Function

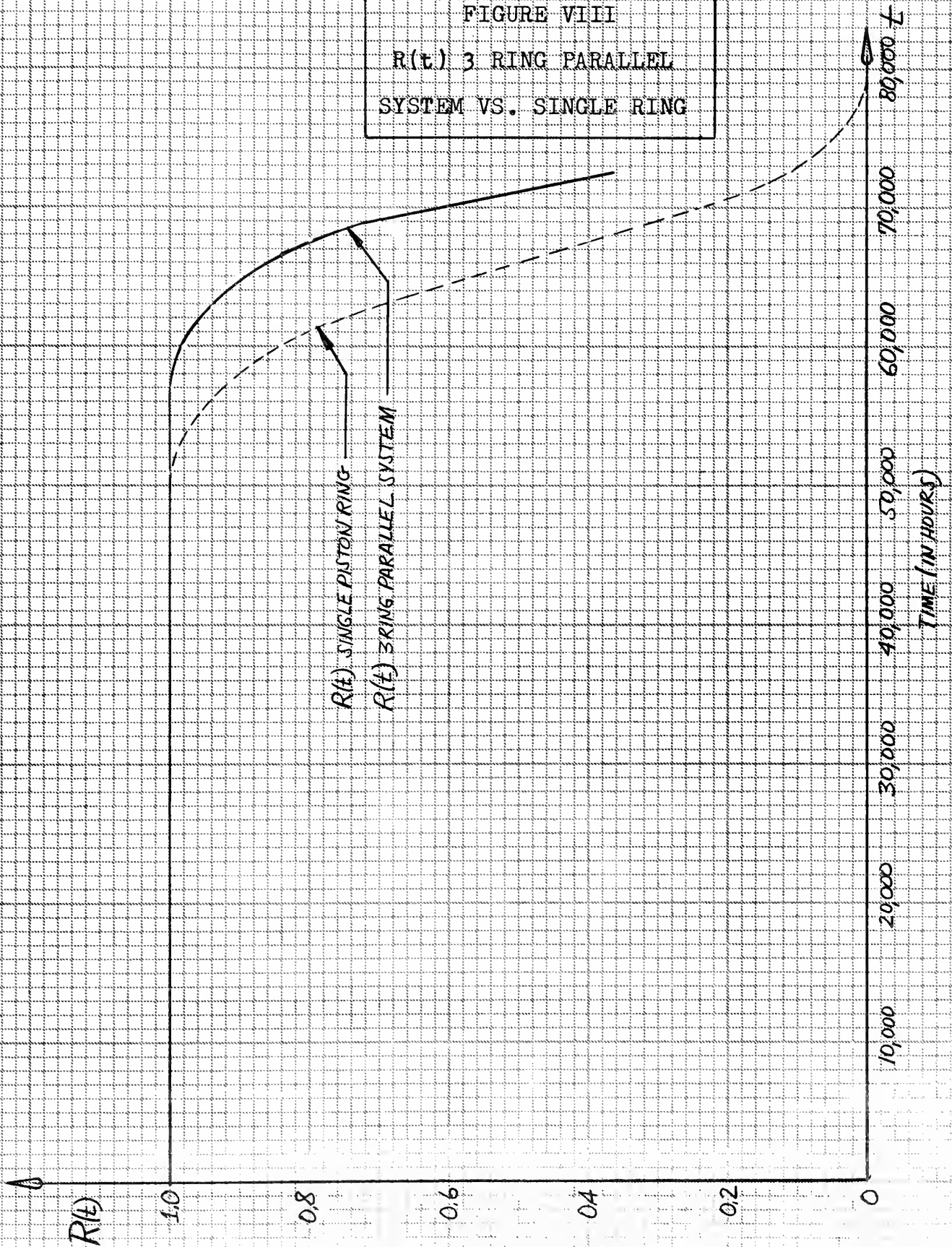
Cyclic endurance wear data, in-service wear data, and material failure report data were available for the main shell bearings. Mechanisms of failure were judged to be out-of-tolerance wear, and a random assortment of in-service problems.

One material failure report listed as possible causes of an in-service main bearing failure:

1. time in service
2. increased pressure resulting from "Top" overhaul,
29 hours past

2. overload during recent full power trial, 6 hours past
"Time in service" could refer to fatigue cracking, metallurgical

FIGURE VIII
 $R(t)$ 3 RING PARALLEL
 SYSTEM VS. SINGLE RING



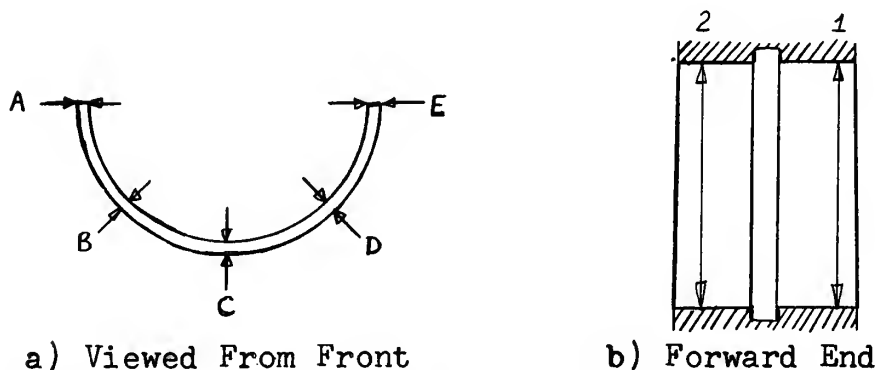
deterioration, foreign deposits, or other phenomena listed in bearing tests, as well as wear. Sliding contact bearing testing machines have been developed, as in [38] .

Material failure reports showed two in-service main bearing failures. Their resume appears in Appendix E, Table IX. A mean, \hat{m} , and L, at 90% confidence, appear in Table X.

Wear measurements for the cyclic endurance test were taken at ten locations along the bearing, as shown in Figure IX, points 1 and 2, A through E.

Figure IX

Location of Wear Measurements
Cummins VT 12M Main Bearing



The maximum wear for each point was recorded for that bearing, and listed in Appendix E, Table XI. Maximum wear occurred on the lower half bearing. From this Table, and the type calculation of Table IV, the \hat{M} , and s parameters for the cycle endurance test wear were calculated, and appear as Table XII.

In-service wear data for seven main bearings were listed in Table XIII, and the parameters appear in Table XIV.

The plot of $R(t)$ for the main bearing that results from the in-service data appears in Figure X.

Development of the Connecting Rod, Piston Pin, and Engine Block Reliability Functions

Wear obviously was not a factor for the engine block itself, or for the connecting rod, excluding both the upper end bushing and the lower end bearing. No measurable wear was recorded along the piston pin diameter, during the cyclic endurance test.

There was no in-service failure of a connecting rod, or piston pin. attributed to the component itself. No block failure was reported that did not result from first failure of another engine component. Because there were no recorded in-service failures of these three components, a point estimate of the mean \hat{m} , could not be made. However, a lower estimate of \hat{m} , L , at 90% confidence was calculated, by the method of Table II, and appear in Table XVI.

Plots of $R(t)$ for these three components appear in Figure XI. Development of the Connecting Rod Bearing, Piston, Connecting Rod Bushing, and Crankshaft Reliability Function

The remaining four central group components presented a problem in the development of their respective reliability functions.

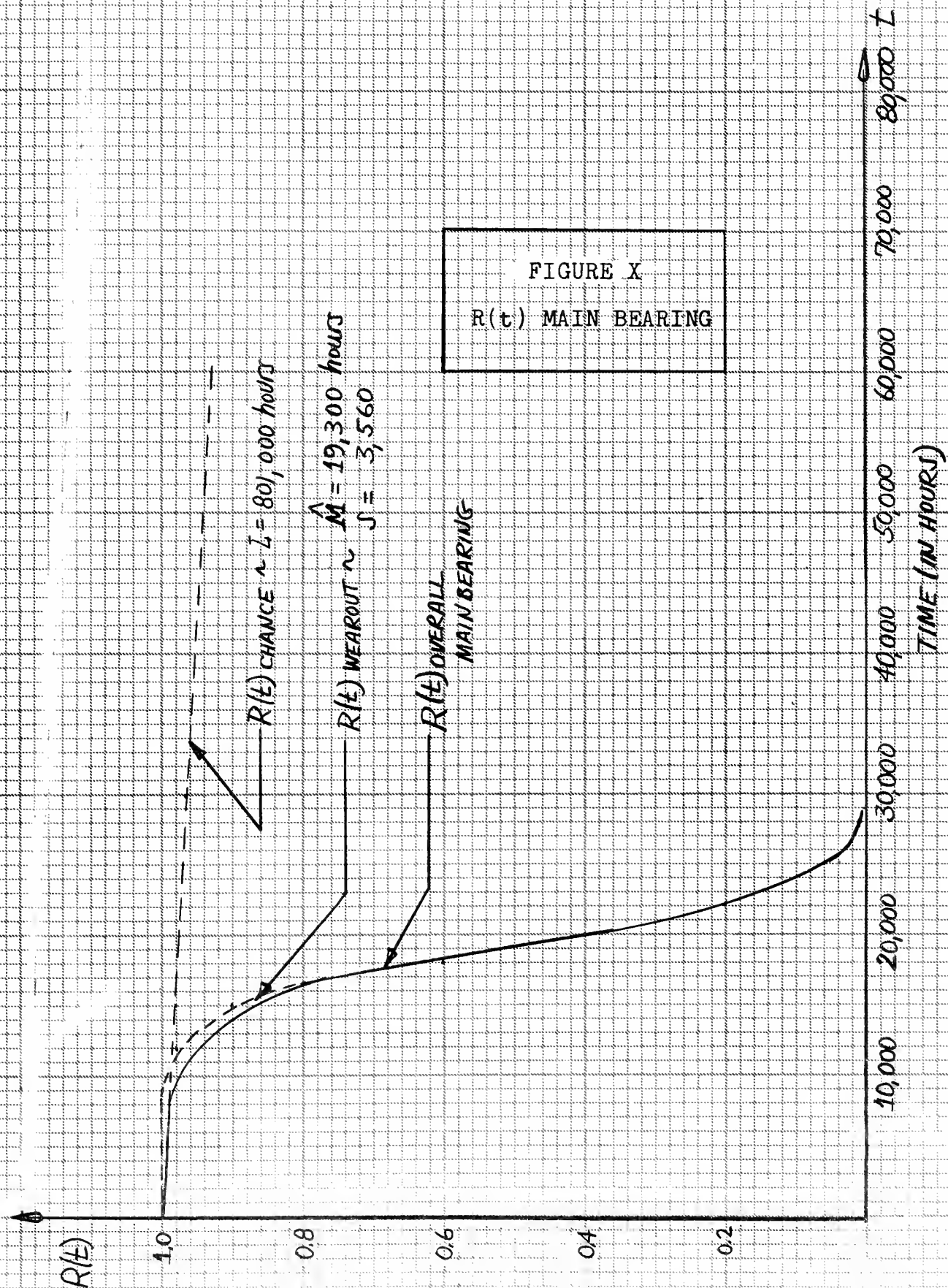
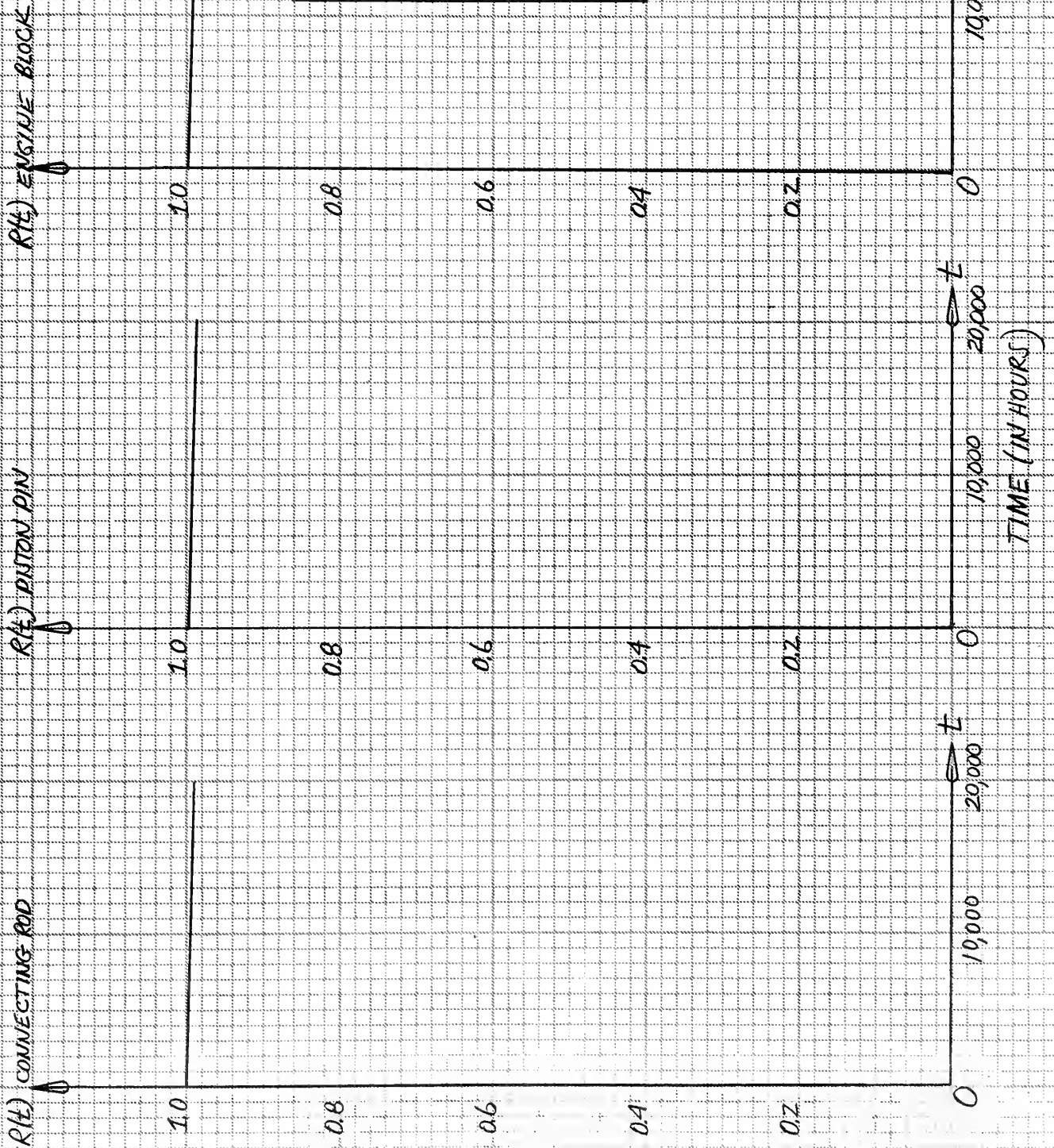


FIGURE X
R(t) MAIN BEARING

FIGURE XI
 $R(t)$ PLOTS
 FOR CONNECTING ROD
 PISTON PIN, AND
 ENGINE BLOCK



High replacement of connecting rod bearings was effected at major overhaul, because of appearance of deposits on the bearing surface. Data taken showed wear to be minor. Three in-service failures were recorded, and appear in Appendix E, Table XV. The plot of $R(t)$ for this component, Figure XII, reflects only the in-service failure rate, because of lack of other data.

Several relatively expensive piston failures occurred, and this component was redesigned. A plot of $R(t)$ cannot be made, but will be assumed as one for the central group analysis.

There was no connecting rod bushing in-service failure, and therefore a lower estimate, L , of the mean was made in Appendix E, Table XVI. Data taken showed wear to be low, but was not sufficient to present. The plot of $R(t)$ for the connecting rod bushing, Figure XII, reflects only the in-service data.

While wear occurred on the main and crank journals of the crankshaft, it was relatively low in comparison to the faster wearing components, and is not presented.

Development of the Central Group Reliability Function

In the procedure it was determined, for accessibility reasons, that the following components comprised a central group: cylinder liner, compression rings, piston, piston pin, connecting rod bushing, connecting rod, connecting rod bearing, crankshaft, main bearing, and engine block. By examining

FIGURE XII
 $R(t)$ PLOTS
 FOR CONNECTING ROD
 BEARING AND BUSHING

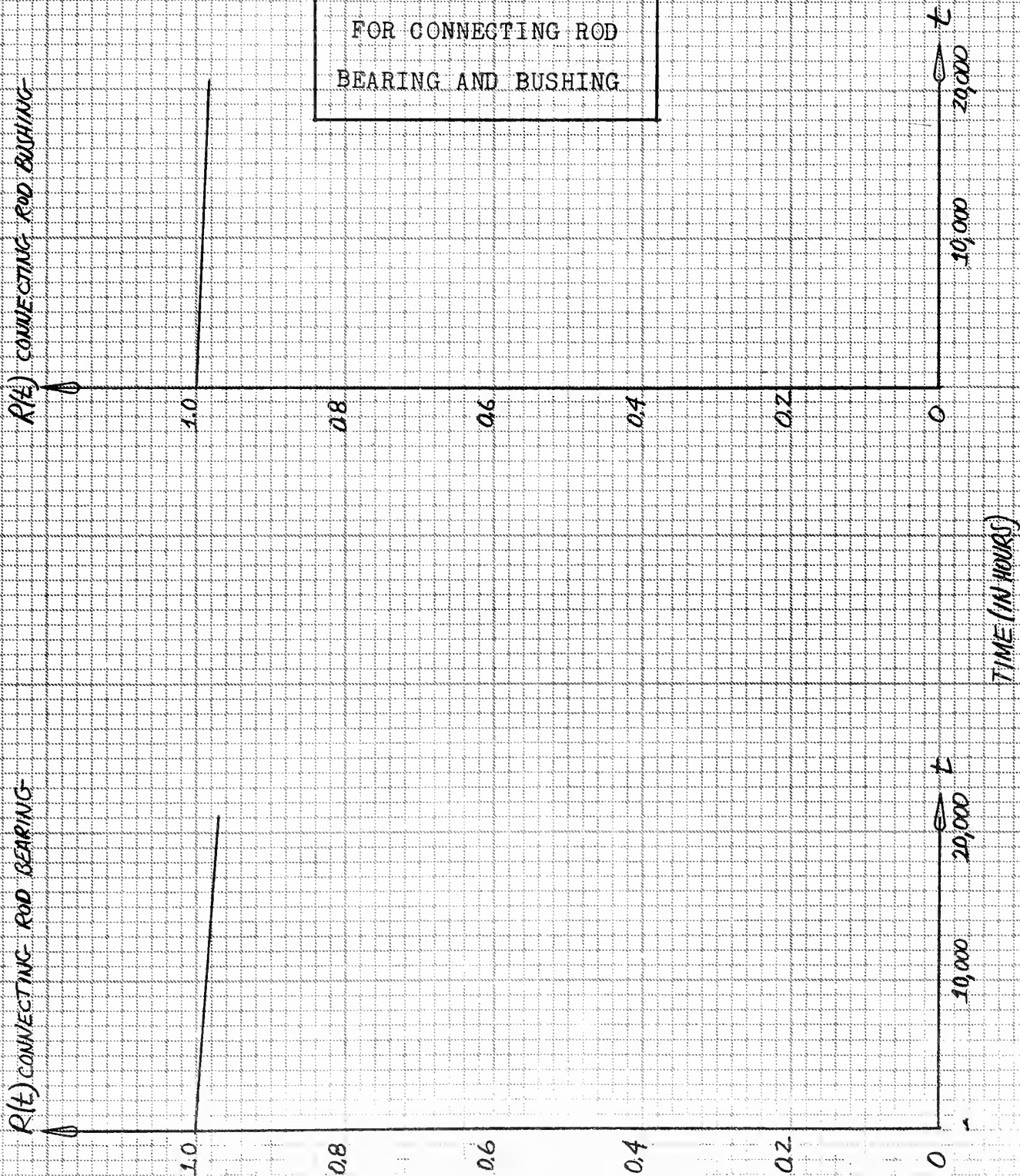


Figure IVb, page 41, and by applying equations (12) and (13), the central group reliability function may be expressed as:

$$\begin{aligned}
 R(t)_{\text{central group}} &= R_{\text{cylinder liner}} \cdot R_{\text{compression ring system}} \cdot R_{\text{piston}} \cdot \\
 &R_{\text{piston pin}} \cdot R_{\text{connecting rod bushing}} \cdot R_{\text{connecting rod}} \cdot R_{\text{connecting rod bearing}} \cdot \\
 &R_{\text{crankshaft}} \cdot R_{\text{main bearing}} \cdot R_{\text{engine block}}
 \end{aligned} \quad (35)$$

Equation (34) should be substituted into (35).

$$R(t)_{\text{compression ring system}} = 3R \left(1 - R + \frac{R^2}{3} \right) \quad (34)$$

Substituting the functions already determined in equation (35), the central group reliability function is obtained. The plot of this function appears in Figure XIII, A and B.

Note that $R(t)$ central group closely approximates the reliability function for the cylinder liner wear. Using equations (32), (27), and (31), developed to determine, within a given reliability requirement, time between major overhauls, we obtain:

$$t_o = \hat{M} - S \left[\frac{t_{\alpha/2; n-1}}{\sqrt{n}} + \sqrt{\frac{k^2 (n-1)}{\chi^2_{1-\alpha; n-1}}} \right]$$

Substituting the values tabulated for cylinder liner wear:

$$t_o = 12,000 - 1,660 \left[\frac{1.71}{4.9} + \sqrt{\frac{1.64 (23)}{14.8}} \right]$$

$$t_o = 7,950 \text{ hours}$$

This value of t_o is indicated in Figure XIII, A and B, by a vertical dotted line. At this value of time, system reliability falls from 0.975 for liner wearout to 0.925 for the overall central group. If a requirement was made that overall group reliability not fall below 0.95 before major overhaul, a halfway compromise between the liner and central group figures, then t_o , time between major overhaul, would equal 6,800 hours.

FIGURE XIII A
R(t) CENTRAL GROUP

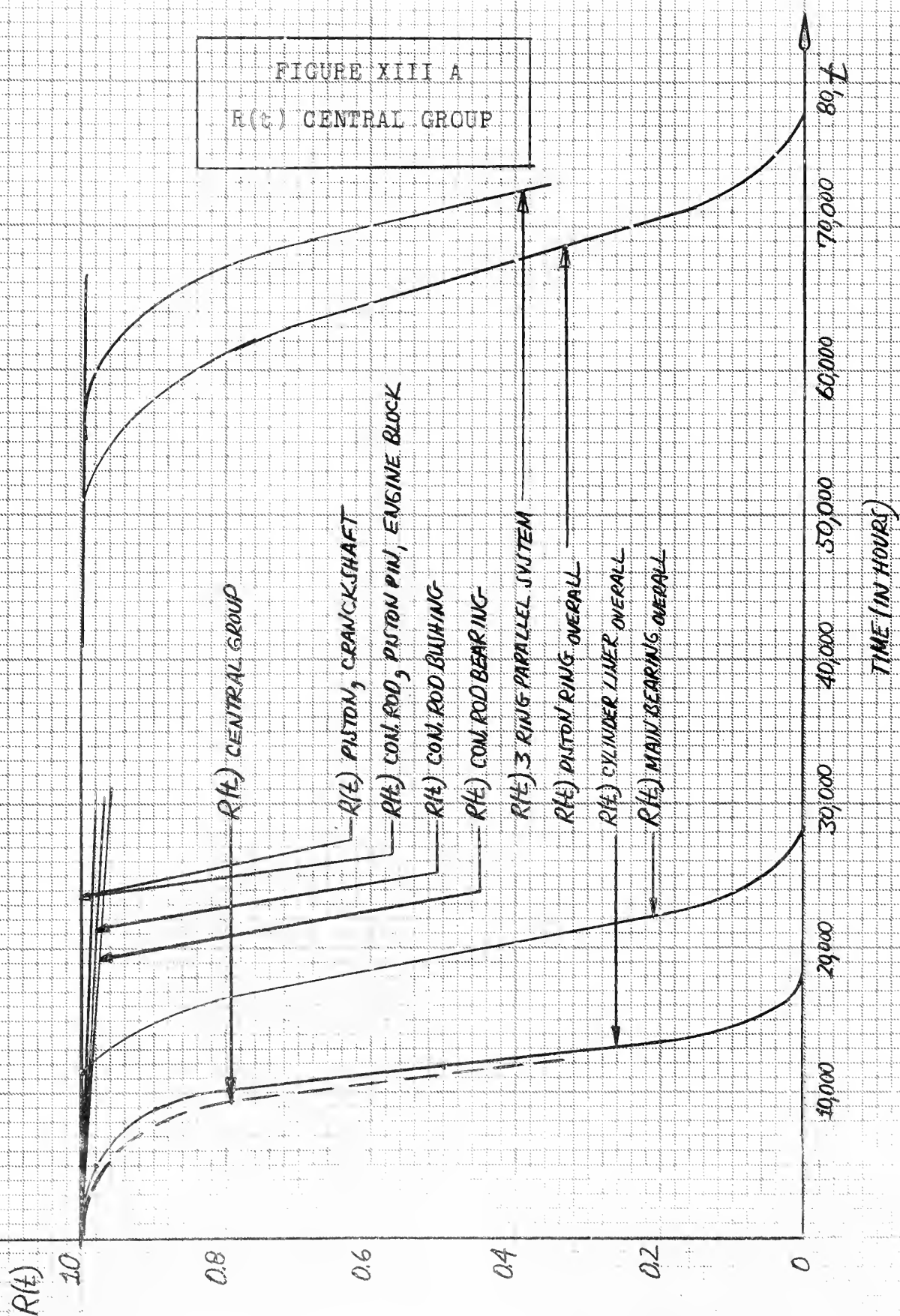
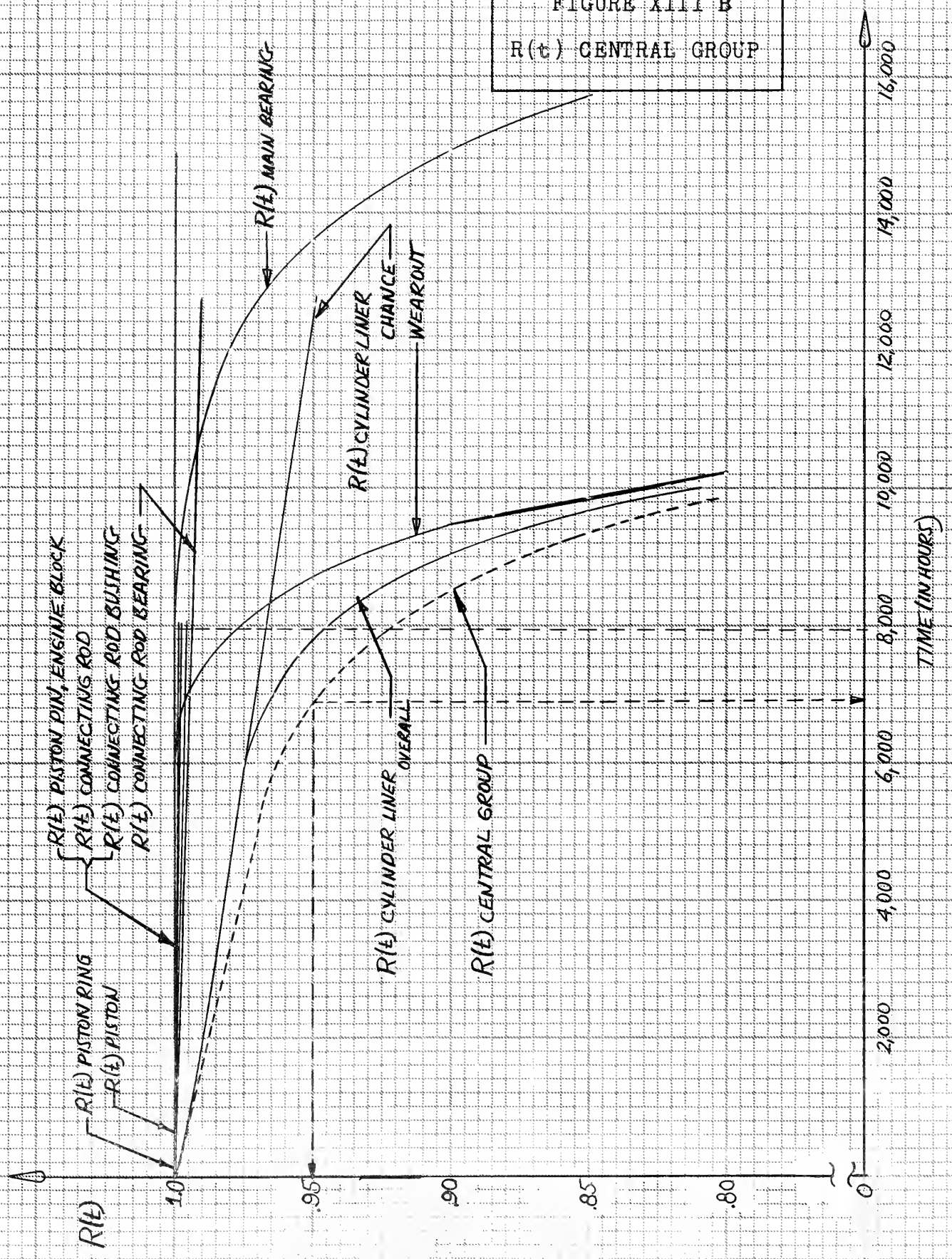


FIGURE XIII B
 $R(t)$ CENTRAL GROUP



DISCUSSION OF RESULTS

Accuracy of the Calculations

The accuracy of calculations is dependent on three assumptions: that the mechanisms of failure can be separated, the parameters of each failure function accurately measured, and a reliability function for an overall group can be determined by solving a flow chart of the group components.

The data obtained are accurate to the established confidence limits, making two assumptions:

1. That unadministered post-factum data, as the present Material Failure Reports, may be used.
2. That the variable parameters in machine operation have averaged out over the time considered.

These assumptions, individually, are discussed on the following pages. As a comparative measuring tool, additional data collection methods are then discussed.

Use of Post-Factum Data

The question, "Why use post-factum data on operation and failure of machine systems and components?", arises naturally. To use this data, we have to assume that:

1. The operating time of the part is recorded exactly in the space provided on the material failure report. This seems to be a valid assumption.

2. The variation in operating conditions, as discussed below, has averaged out for the entire sample. This seems to be a valid assumption.

3. All failures that occurred were reported. The veracity of this assumption is open to conjecture.

The problems in laboratory testing are:

1. Time
2. Cost
3. The identification of the mechanism of failure, i.e. chance, wearout, etc.
4. Duplication, in the laboratory, of in-service operating conditions.

A trial of post factum analysis is recommended, due to the problems of testing.

Variable Parameters in Machine Operation

The following parameters, if changed, would affect the data gathered on the components and machine system of this example, the CUMMINS VT 12M diesel engine:

1. Design
2. Level of operation, that is: rpm, bmep, back pressure, temperatures
3. Lubricating oil: type, purification equipment
4. Fuel oil
5. Environmental conditions: ambient temperature, particles, such as dirt, in the air, humidity, etc.

We have assumed, by grouping the Material Failure Reports, that over the time considered, each component, and the machine system, were exposed to a uniform stress level.

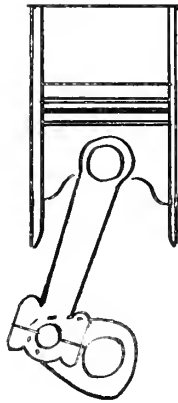
Additional Data Collection Methods

There are three areas where data could be gathered to assist in maintenance schedule optimization:

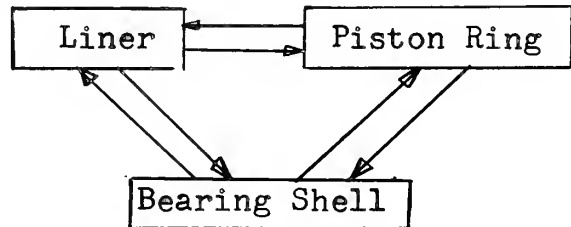
1. Analysis
2. Laboratory testing
3. Administered post-factum feedback.

The function $R(t)$ overall system may be obtained analytically, in the future, by creation of a mathematical model of part interaction. Consider the faster wearing diesel parts: cylinder liners, piston rings, and connecting rod bearing shells. These components all interact (Figure XIV a) or, in other words, the wear rate of one component affects the rate of another. We may construct a flow chart (Figure XIV b) of this wear, and analyze it as a Markov process, as has been proposed [23] . This method may produce, for the group of components considered, an $R(t)$ group, which would yield a scientifically scheduled maintenance program. This would be a revolutionary breakthrough, as a successful analysis of this group could be reapplied, using computerized techniques, to any size machine system. However, this Markov process cannot be analyzed without data.

Figure XIV
Diesel Engine Component Interaction



a) Physical Diagram



b) Flow Chart

Another method of obtaining $R(t)$ by analysis was mentioned in [27] , and illustrated by Figures 30 and 31 of [17] .

Laboratory measurements and testing may develop estimates of M , m , and \bar{O} for the reliability functions of the various mechanisms of failure. The size of the experiment will determine the range of these estimates, to a given confidence level, as discussed in the Procedure. If the estimate of one failure mechanism parameter is more than an order of magnitude greater than the estimate of a second mechanism of the same component, then precise measurement of the second mechanism is really unnecessary, as pointed out on page 36 and in Appendix D, Part C. There seem to be four techniques available in the laboratory that would be helpful in obtaining data for the machine system used as example in this thesis:

1. Mechanical wear (bore gauge, etc.) measurement
2. Radioactive tracer technique for wear measurement
3. Spectographic analysis of lubricating oil, for wear products
4. Test machines (bearing tester, for example)

Laboratory test operation of the system, with interim measurements of wear, simulates field operation. It has the advantage of supervision by experienced engineers, but is very time consuming and expensive.

Radioactive tracer wear measurement techniques have been used to provide an accelerated method of testing the influence of various factors on wear in diesel engines [34] . This technique is applicable to engine components where metallurgy and size permit irradiation in a nuclear reactor. It could be used for more accurate examination of the time dependency of wear, and the relation of wear of one part to the condition of the adjoining part. Recent studies have related piston ring and cylinder liner wear separately to the following variables: power output, engine speed, fuel characteristics, lubricating oil properties, air cleaners, engine conditions, and part metallurgy [34, 39, 40] .

After irradiation in a reactor, the components are installed in the engine. The newly created isotopes release energy by radiation, measured by disintegrations per second. The activity depends on five variables, as given by [39] .

$$A = N\sigma\phi (1-e^{-\Lambda t}) \quad (36)$$

A = Activity, in disintegrations/sec.

N = No. of target atoms in material being irradiated

σ = Material cross section, barns

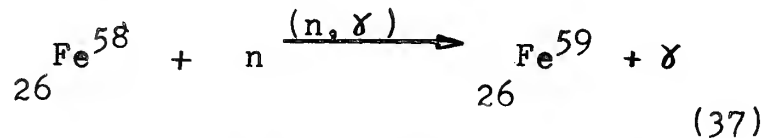
ϕ = Neutron flux of irradiation, n/cm²/sec.

Λ = Disintegration constant

t = Irradiation time

The counting of wear particles entrained in engine lubricating oil is simplified if the isotope available has a high level of Gamma ray energy. Time to evaluate wear rates is determined by isotope half-life. Half-life also dictates whether shielded storage or special disposal will be necessary after completion of the tests.

For short duration tests, cast iron diesel cylinder liners would follow a neutron - gamma (n, γ) reaction.



The rate of decay of an isotope would be proportional to the number of radioactive atoms of the considered isotope. Λ is called the decay constant.

$$\frac{dN}{dt} = -\Lambda N \quad (38)$$

Integrating between the time when the number of atoms present is N_0 and N

$$\int_{N_0}^N \frac{dN}{N} = -\Lambda \int_0^t dt$$

$$\ln \frac{N}{N_0} = -\Lambda t$$

$$N = N_0 e^{-\Lambda t} \quad (39)$$

The half life, or time for the number of radioactive atoms of the particular isotope to decay to half its initial value, and hence independent of the absolute quantity of atoms, is given by:

$$\frac{N}{N_0} = \frac{1}{2} = e^{-\Lambda(t \frac{1}{2})}$$

$$t \frac{1}{2} = \frac{\ln 2}{\Lambda} \quad (40)$$

If we desire to test the wear rate of a component fabricated from a particular alloy, the counting technique is complicated by the various half-life periods. With careful instrumentation we can read the decay of only the more radioactive elements, measuring the activated wear particles. It is obvious some elements are more suited for this study than others.

The other laboratory methods listed on page 64 will not be discussed further.

The third avenue mentioned on page 62 to obtain data was administered post-factum feedback. This method differs from that of the Procedure in that it would be planned and administered, for this purpose. If a controlled flow of history from operating engines is to be obtained, a feedback system of information on operation must be provided. This feedback must be administered by a standardized maintenance management program. This is to validate the assumption that all failures that occurred were reported.

An experiment was conducted in 1950 [41] where 120 sliding contact bearings were sent to Fleet ships for in-service test. The bearings proved to be a long life component, certainly far beyond the major overhaul interval, t_o , of the parent machine system. Beyond this fact, little was learned because few bearings were examined upon ultimate removal, and the experiment was almost as forgotten by the experiment designer as it was by the Fleet units, who had gone through many changes in personnel.

The U.S. Navy established a post-factum system on the USS LOWRY to feed back data on the operation of standardized preventive maintenance. More recently a standardized preventive maintenance management system has been established for eight more U.S. Navy ships.

CONCLUSIONS

Techniques for development of reliability functions for mechanical components, and for determining optimum major overhaul intervals for a mechanical system, are the small contributions attempted in this thesis to the growing field of reliability and maintainability of mechanical systems.

1. Accuracy of reliability functions produced for mechanical components depends on the validity of the four steps listed on page 37 , developed as a procedure to obtain the functions. Care must be taken in applying each step.

2. Available data should reveal the mechanisms of failure that reasonably could cause failure, and provide relative measurement of the characteristic parameters of each mode of failure.

3. Analysis has shown that a reliability function for a mechanical component may be determined by rough data measuring the relative frequencies of the various modes of failure of that component. The time difference between the parameter of the major mode, and others, may be of an order of magnitude, or more, in the sense of Appendix D, Part c. If this is the case, the reliability function for the component may be determined by evaluating precisely the parameters of the principal failure modes.

4. The data used in this thesis is limited in size, but gives a definite measure of the relative size of the principal parameters, which, as shown in Appendix D, part c, dominate the component function. The necessary data measuring these principal failure modes may be more available than thought. Once the principal failure modes are identified, further data could be obtained to more precisely evaluate the parameters of these modes. Upon determining which component functions rule the component group function, further data could be obtained from these components.

5. Assumptions had to be made for some in-service parameters, from examination of laboratory data. If this thesis had been planned over a longer period of time, this information could be obtained, at small cost, for the components with lowest reliabilities. Appendix D, part c, again, dictates that we are more concerned with these components.

6. The concept of accessibility is assumed to be the key to determination of the reliability function for the central group.

7. The reliability function for the central group can be obtained through application of the series and parallel laws of reliability, through a flow chart. Other methods are presented in the Discussion of Results, and in Recommendations, for further research. The central group, or system, function yields an analytical method for determining optimum intervals for major

overhaul, dependant on the time rate of change of system reliability.

8. Reliability and maintainability of mechanical systems are important parameters for potential savings in time and funds through scheduling of major overhaul, as investigated in the Results. Reliability and maintainability concepts are also an integral part of preventive and corrective maintenance. It must be realized that potential savings are computed by subtracting the cost of the design, management, and execution of the data feedback system from the total savings wrought by the new overhaul schedule.

RECOMMENDATIONS

From this initial investigation of methods to produce component reliability functions, group function, and optimum major overhaul cycles, the following topics appear promising for study.

1. Examine a method to obtain the central group function by means of a Markovian flow graph, depicting the interacting parts, and their relationships to each other. This was covered briefly in Discussion of Results.

2. Examine thoroughly all data collection methods available, including administered and unadministered feedback, and controlled tests. Time and cost would be controlling factors.

3. Investigate the spare part inventory, as associated with component reliability functions, and major overhaul cycles.

4. Investigate major overhaul schedule optimization against costs, showing cost over system life (major overhaul cycles).

5. Develop a concept of machine availability, to assist management in operational planning. Show how the number of systems available in a year differ for various overhaul cycles.

6. Investigate the relationship of machine system reliability to major overhaul schedule, parts inventory, system availability, costs of overhaul cycle and part inventory, and other

parameters stipulated by machine system management.

7. Study overhaul cycle schedule for: synchronization with other machine systems, or entire ship schedules; special problems of systems located at isolated locations; and systems whose reliability has been increased by stand-by machinery, in the sense of Figure Ib.

The following steps should be adopted to evaluate the applicability of major overhaul scheduling optimization for a mechanical system:

1. Perform a theoretical reliability and maintainability analysis on two machine systems:

a) the in-service system upon which large sums of maintenance and repair funds are budgeted

b) a system on a new class of ships.

2. Gather data on the systems as follows:

a) for the in-service system; from past failure reports, from thorough wear inspection of a sample of in-service engines, and from a designed feedback system.

b) for a system in a new class of ships, from manufacturers guarantees of a lower limit, L , on component mean life, or from a previous system information.

Use the data to obtain the cycle of major overhaul, t_o . Compute the cost of maintenance, overhaul, and availability under this major overhaul cycle. Compare this cost with:

- a. the cost of the machine systems' existing overhaul cycle
- b. the cost of the new machine systems' overhaul cycle.

Compare the theoretical reliability of the machine systems studied under the respective overhaul cycles.

3. Perform steps one and two by in-house people, or a consultant independent of the machine system manufacturer. If it appears that considerable time and money could be saved by the major overhaul cycle derived for a machine system, the following steps should be taken.

4. Establish a tentative standard maintenance schedule, based on the major overhaul cycle derived, with complete instructions.

5. Initiate an operational data feedback system, as discussed on page 67 for the machine system.

6. Establish a Maintenance Management Desk, to act as a data library to perform the last two steps, and in the future, the first three steps.

APPENDICES

APPENDIX A

A Typical Material Failure Report

Reporting Unit	District	Date of Report	Date of Fail
Identification of Part Failing	Man'f'r	Part, No.	Time in Use
Ident. of Machine System	Man'f'r	Model No.	Serial No.
Est. Cost of Repairs	Est. Hours for Repairs		
Reference Letter (if any)			
Description of Failure			
Description of Damage Resulting from Failure			
Cause and Remedy of Failure			
Remarks and Recommendations (Frequency of Failure)			
District Engineer's Comment			

APPENDIX B

A Mathematical Method for Obtaining the Reliability Function

The following notation is defined on page 20 : $R(t)$, N_s , N_f , N_o

$$N_o = N_s + N_f \quad (B1)$$

$$R(t) \equiv \lim_{N_o \rightarrow \infty} \frac{N_s}{N_o} = \frac{N_o}{N_o} \quad (B2)$$

$$R(t) = 1 - \frac{N_f}{N_o}$$

Rearranging

$$\frac{dR(t)}{dt} = - \frac{1}{N_o} \frac{dN_f}{dt} \quad (B3)$$

$$\frac{dN_f}{dt} = - N_o \frac{dR}{dt}$$

$$\frac{dN_f}{dt} = \frac{d(N_o - N_s)}{dt}$$

And from (B3)

$$\frac{dN_f}{dt} = - N_o \frac{dR}{dt}$$

Dividing through by N_s ; $\frac{1}{N}$

$$\frac{dN_f}{dt} = - \frac{N_o}{N_s} \frac{dR}{dt}$$

The term $\frac{dN_f}{dt}$ can be interpreted as the number of components failing in the time interval dt , between time t and $t + dt$.

The term $\frac{1}{N_s} \frac{dN_f}{dt}$ represents the instantaneous probability of failure per one remaining component. This is defined on page 23 as the instant failure rate, is called $\lambda(t)$, and may be constant or a function of time.

$$\lambda(t) \equiv \frac{1}{N_s} \frac{dN_f}{dt} = - \frac{N_o}{N_s} \frac{dR}{dt} \quad (B4)$$

but $R = \frac{N_s}{N_o}$

$$\lambda(t) = - \frac{1}{R(t)} \frac{dR(t)}{dt}$$

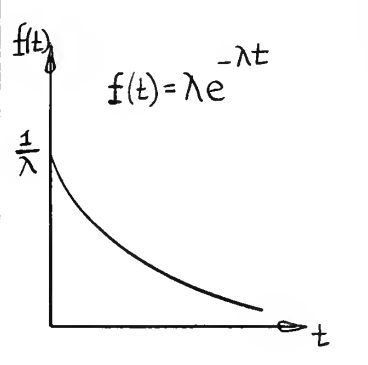
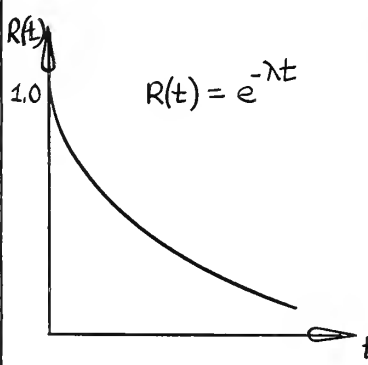
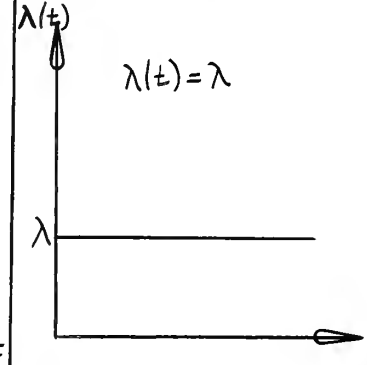
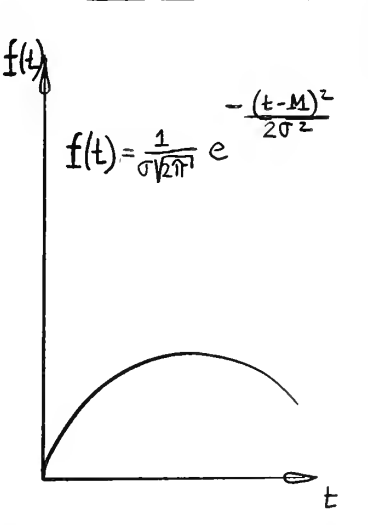
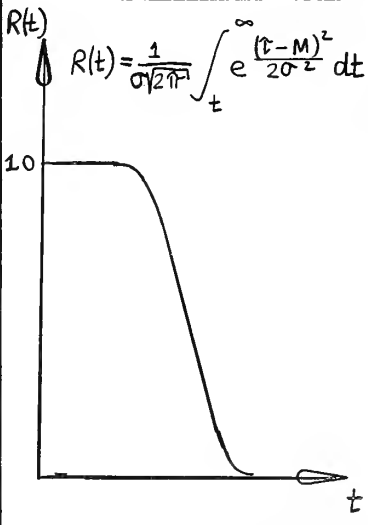
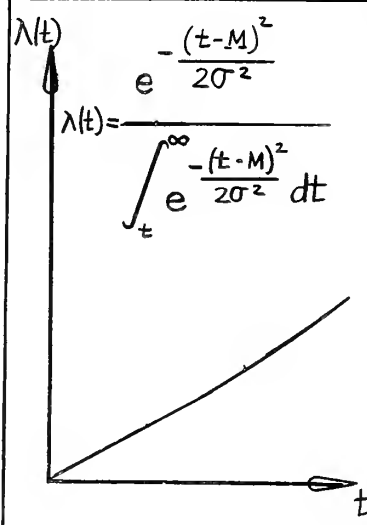
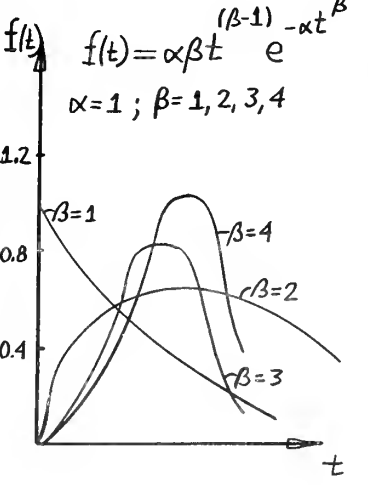
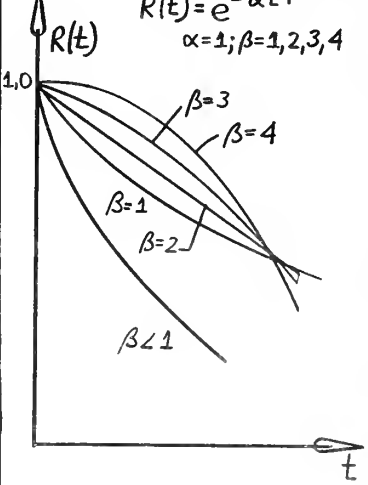
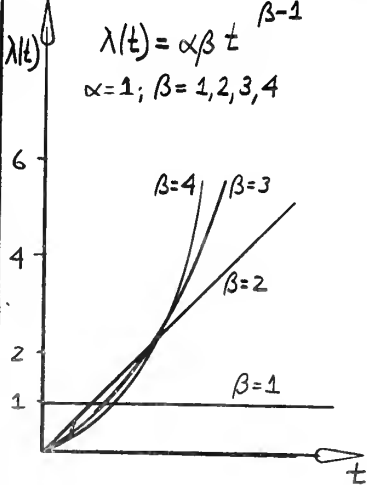
Integrating $\ln R(t) = - \int_0^t \lambda(t) dt$

Taking both sides as exponential powers, and using the boundary condition that at $t=0$, $R=1$,

$$R(t) = \exp \left[- \int_0^t \lambda(t) dt \right] \quad (3)$$

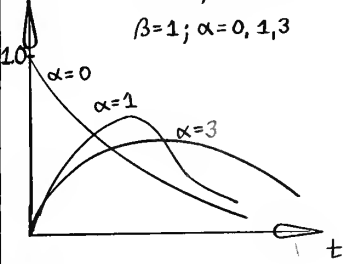
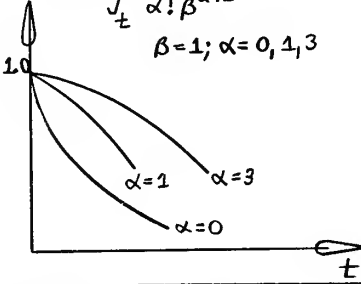
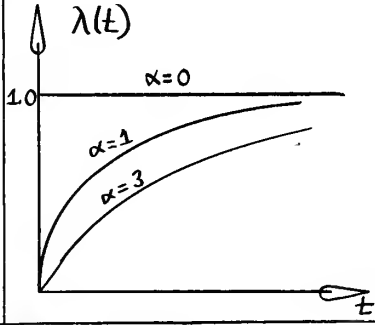
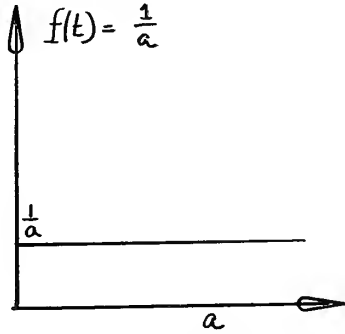
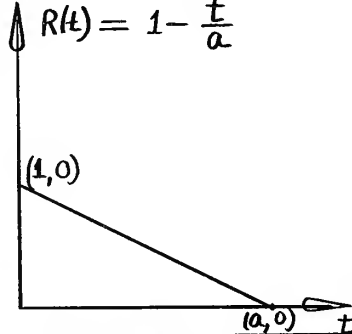
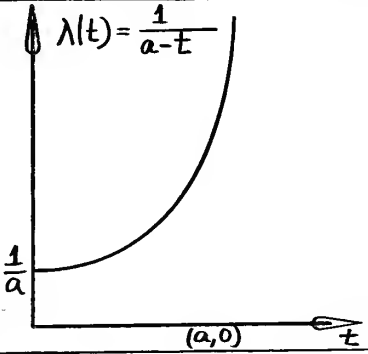
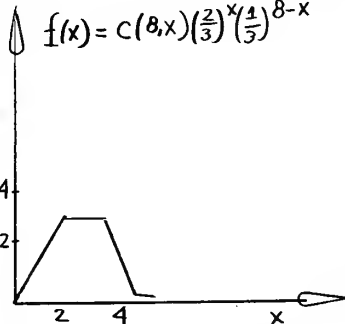
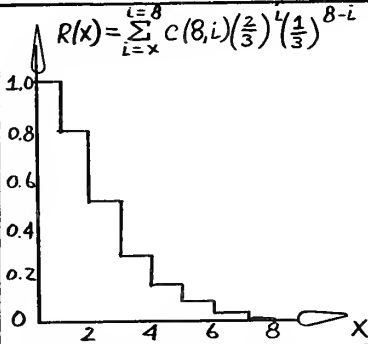
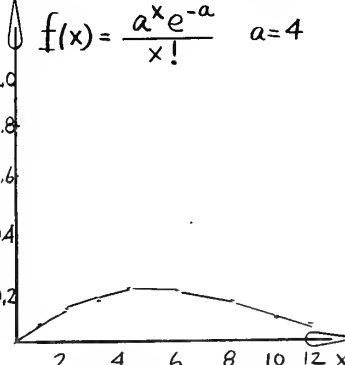
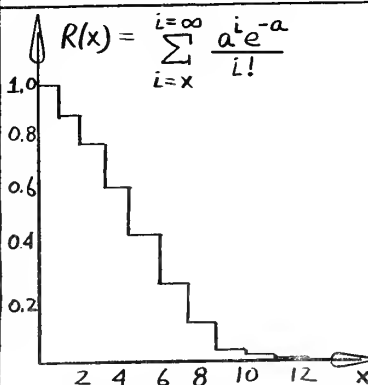
APPENDIX C

A. Table of the More Common Functions

Name	Failure Density Function $f(t)$	Reliability Funct. $R(t)$	Instant Fail. Rate $\lambda(t) = f(t) / R(t)$
Exponential	 $f(t) = \lambda e^{-\lambda t}$	 $R(t) = e^{-\lambda t}$	 $\lambda(t) = \lambda$
Normal or Gaussian	 $f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-M)^2}{2\sigma^2}}$	 $R(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_t^{\infty} e^{-\frac{(t-M)^2}{2\sigma^2}} dt$	 $\lambda(t) = \frac{e^{-\frac{(t-M)^2}{2\sigma^2}}}{\int_t^{\infty} e^{-\frac{(t-M)^2}{2\sigma^2}} dt}$
Weibull	 $f(t) = \alpha \beta t^{(\beta-1)} e^{-\alpha t^\beta}$ $\alpha=1; \beta=1, 2, 3, 4$	 $R(t) = e^{-\alpha t^\beta}$ $\alpha=1; \beta=1, 2, 3, 4$	 $\lambda(t) = \alpha \beta t^{\beta-1}$ $\alpha=1; \beta=1, 2, 3, 4$

APPENDIX C (Con't)

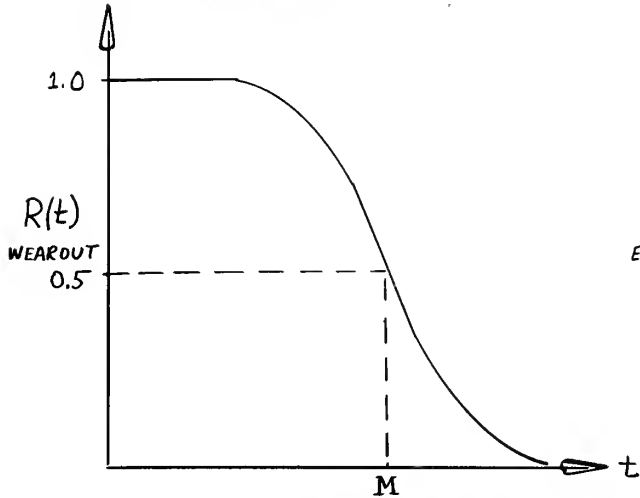
A Table of the More Common Functions

Name	Failure Density Function $f(t)$	Reliability Funct. $R(t)$	Instant Failure Rate $\lambda(t) = f(t) / R(t)$
Gamma	$f(t) = \frac{1}{\alpha! \beta^{\alpha+1}} t^{\alpha} e^{-t/\beta}$ $\beta=1; \alpha=0, 1, 3$ 	$R(t) = \int_t^{\infty} \frac{1}{\alpha! \beta^{\alpha+1}} t^{\alpha} e^{-t/\beta} dt$ $\beta=1; \alpha=0, 1, 3$ 	$\lambda(t)$ 
Rect- angu- lar	$f(t) = \frac{1}{a}$ 	$R(t) = 1 - \frac{t}{a}$ 	$\lambda(t) = \frac{1}{a-t}$ 
Binomial	$f(x) = C(8,x) \left(\frac{2}{3}\right)^x \left(\frac{1}{3}\right)^{8-x}$ 	$R(x) = \sum_{i=x}^8 C(8,i) \left(\frac{2}{3}\right)^i \left(\frac{1}{3}\right)^{8-i}$ 	NOT APPLICABLE
Poisson	$f(x) = \frac{a^x e^{-a}}{x!} \quad a=4$ 	$R(x) = \sum_{i=x}^{\infty} \frac{a^i e^{-a}}{i!}$ 	NOT APPLICABLE

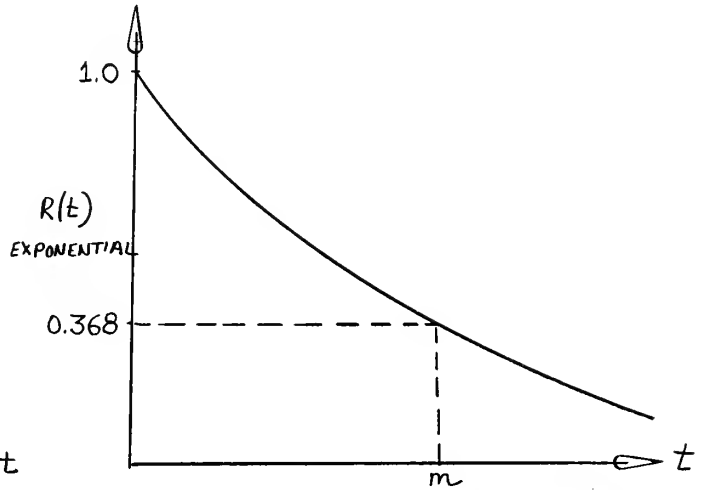
APPENDIX D

Effect of Reliability Product Rule

a) Individual Functions

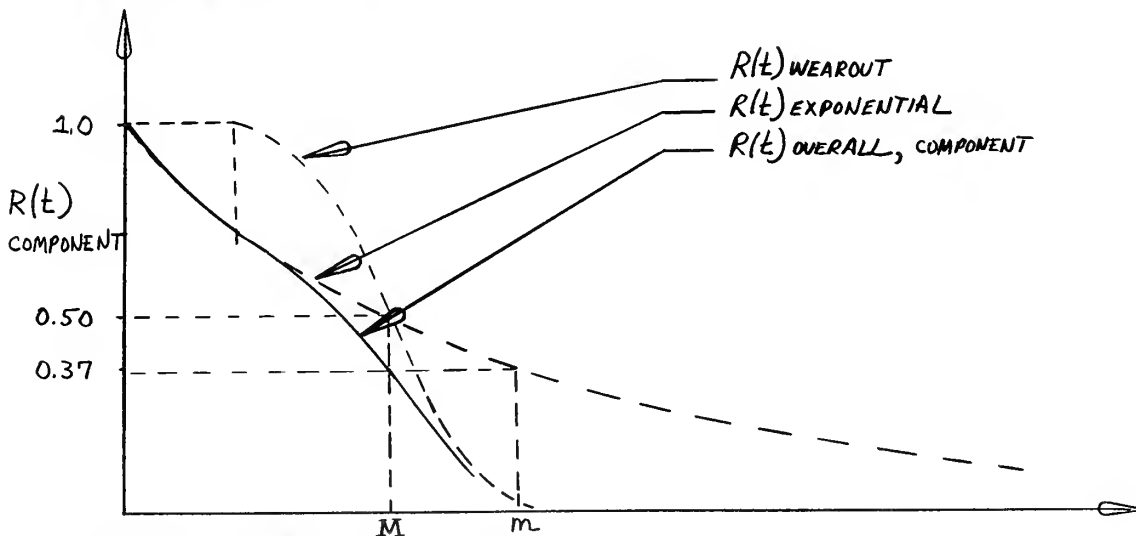


For normal (wearout, etc.) distribution. Note slope, and note that $R(t)$ reaches 0.5 at mean life, M .



For exponential (chance, etc.) distribution. Note slope, and note that $R(t)$ reaches 0.368 at the MTBF, m .

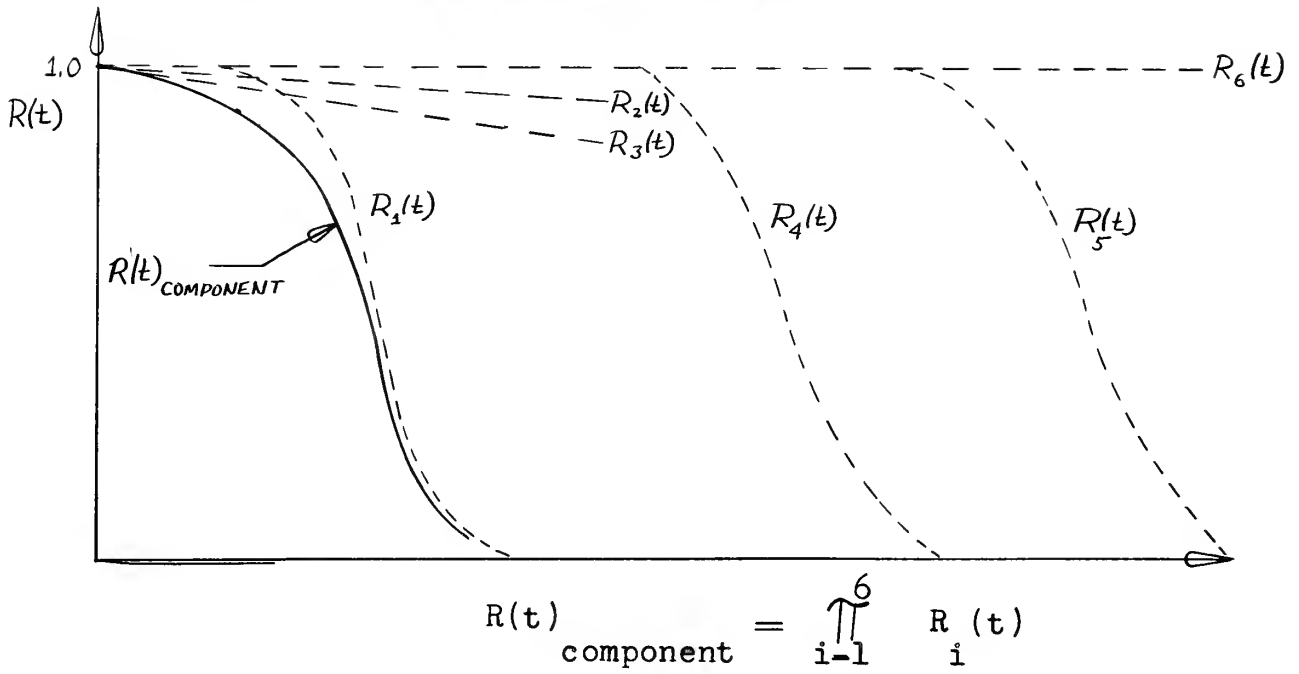
b) Product Rule



Effect of equation (33)

APPENDIX D (CONTINUED)

c) $R(t)$ Tends to be Weighted by Lowest $R(t)$



APPENDIX E

Summary of Data and Calculations

Table I

Material Failure Report Data

VT 12M Cylinder Liner

DATE	UNIT	ENG. #	HOURS RUN	CAUSE - REASON NOTICED -ACTION	COST (\$)	REPAIR TIME (HOURS)
8/15/55	95302	2	1950	Liner scored - noticed by loss of compression. Failure included in analysis.	\$120.	--
2/28/57	95306	2	2863	Liner backs showed large areas of pin-hole cavitation. Liner wear was .001" or less. Noticed on scheduled major maintenance. Therefore failure will not be included in analysis. Liners were renewed.	250.	500
1/11/57	95306	4	2	Liner backs showed large areas of pin-hole cavitation. Liner wear was .001" or less. Noticed on scheduled major maintenance. Therefore failure will not be included in analysis. Liners were renewed.	250.	500
6/24/57	95305	3	3450	Crack was found in a cylinder liner. Pitting noticed on water side of failed liner. Noticed through excessive water in lubrication oil. Failure included in analysis.	25.	15

Table I (Continued)
Material Failure Report Data
VT 12M Cylinder Liner

DATE	UNIT	ENG. #	HOURS RUN	CAUSE & REASON NOTICED - ACTION	COST (\$)	REPAIR TIME (HOURS)
8/24/57	95305	2	3666	Crack was found in a cylinder liner. Pitting noticed on water side of failed liner. Noticed through excessive water in lubrication oil. Failure included in analysis.	30	15
9/14/57	95311	4	360	Crack was found in a cylinder liner. Pitting noticed on water side of failed liner. Noticed through excessive water in lubrication oil. Failure included in analysis.	300	48
11/18/57	95305	3	4017	Crack was found in a cylinder liner. Pitting noticed on water side of failed liner. Noticed through excessive water in lubricating oil. Failure included in analysis, as engine had not been through "major" maintenance, because of fund shortage.	30	15
2/16/59	95326	1	400	Liner found scored. Noticed by lack of compression. The top compression may have been seated improperly on installation. Failure included in analysis.	150	200

Table I (Continued)
Material Failure Report Data
VT 12M Cylinder Liner

DATE	UNIT	ENG. #	HOURS RUN	CAUSE-REASON NOTICED-ACTION	COST (\$)	REPAIR TIME (HOURS)
10/23/61	95321	3	0	Upon completion of overhaul, cracked liner was discovered after futile attempt to jack engine by hand. Failure was past first "major" maintenance, and therefore not included in analysis.	15.	12
2/5/62	95311	4	8	Cracked liner was attributed to a bad casting of the liner. Failure not included in analysis, as past first "major" maintenance.	--	8
7/12/62	95310	2	1308	Six liners on one bank were found cracked under upper lip. The cracked liners were believed to contribute to severe damage to connecting rod and main bearings. Liner failures included in analysis.	2,000.	--
7/30/62	95318	2	2974	Liner cracked. Waterside pitting noted. Discovered by heavy condensation coming from the locker arm breathers. Failure included in the analysis.	86.	24
2/11/63	95327	4	2626	Liner cracked and pitted. Believed to be human error, because of excessive fuel oil pressure.	600.	102

Table II
Cylinder Liner Chance Failure Calculation

A. SAMPLE CALCULATION FOR CHANCE DATA, TABLE I

by equation (18)

$$m = \frac{nt}{r} = \frac{T}{r}$$

$$n = 12(4) \cdot (35) \quad (\text{see page 16})$$

$$t = 3,000 \text{ hours}$$

$$T = nt = 5.04(10)^6 \quad r = 14$$

(see Table I)

$$m = \frac{5.04(10)^6}{14}$$

$$m = 360,000 \text{ hours} = 3.6(10)^5 \text{ hours.}$$

B. RANGE OF MEAN

at 90% Confidence Level

by equation (21)

$$L = \frac{2T}{\chi_{\frac{\alpha}{2}}^2; 2r + 2}$$

$$L = \frac{10.08(10)^6}{43.8} = 2.46(10)^5 \text{ hours}$$

Table III
Cylinder Liner Wearout Data
From

Cyclic Test Mean and Standard Deviation of Cylinder Life, Duty A
Cummins VT 12M Engine

<u>1</u> PISTON NO.	<u>2</u> W WEAR (598 hrs.) (10) ⁻⁴ in.	<u>3</u> W WEAR RATE in/10 ³ hrs.	<u>4</u> t _i wearout LINER LIFE FROM WEAR	<u>5</u> it - M ¹ LINER LIFE DEVIATION (hours)	<u>6</u> it - M ¹²
1R	6	1.00(10) ⁻³	5000	2040	416(10) ⁴
2R	10	1.67(10) ⁻³	3000	40	0(10) ⁴
3R	14	2.34(10) ⁻³	2140	820	67(10) ⁴
4R	10	1.67(10) ⁻³	3000	40	0(10) ⁴
5R	13	2.18(10) ⁻³	2300	660	43.5(10) ⁴
6R	13	2.18(10) ⁻³	2300	660	43.5(10) ⁴
1L	12	2.00(10) ⁻³	2500	460	21(10) ⁴
2L	13	2.18(10) ⁻³	2300	660	43.5(10) ⁴
3L	12	2.00(10) ⁻³	2500	460	21(10) ⁴
4L	12	2.00(10) ⁻³	2500	460	21(10) ⁴
5L	7	1.17(10) ⁻³	4270	1310	172(10) ⁴
6L	8	1.34(10) ⁻³	3730	770	59(10) ⁴
<u>TOTALS</u>			35,540		907(10) ⁴

Table IV
Cylinder Liner Wearout Calculations
Cummins VT 12M Engine

A. SAMPLE CALCULATIONS FOR WEAROUT DATA, TABLE 3

$$1. \quad \frac{[\text{WEAR } (10)^{-4} \text{ (in)}] \cdot (10)^3}{\text{OP. TIME} = 5.98(10)^2 \text{ hrs.}} =$$

$$\frac{\text{Col 2} \cdot (10)^3}{5.98(10)^2} = \text{WEAR RATE} = \text{in.}/(10)^3 \text{ hrs} = \text{Column 3}$$

$$2. \quad \frac{\text{LINER CLEARANCE}}{\text{WEAR RATE}} =$$

$$\frac{\overset{X_e}{\underset{W}{\cdot}} = .005''}{\text{Col 3}} = \text{LINER LIFE} = \text{Column 4} = t_i$$

B. MEAN AND STANDARD DEVIATION, CYCLIC LOAD TESTS

$$\text{by equation (25)} \quad \hat{M} = \frac{\sum_{i=1}^{12} t_{iw}}{r \text{ wear}} = 2,960 \text{ hours}$$

$$\text{by equation (26)} \quad s \equiv \hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{12} (|t_{iw} - M|)^2}{r \text{ wear}}} = 830 \text{ hrs.}$$

at .90 Confidence Level

$$\text{by equation (28)} \quad L = \hat{M} - (t_{\alpha/2; n-1}) \frac{s}{\sqrt{n}}$$

Table IV
Cylinder Liner Wearout Calculations
Cummins VT 12M Engine

C. MEAN AND STANDARD DEVIATION, SERVICE OPERATION

by in-service major overhaul data

for 24 cylinders

$$\bar{W} = 0.001250"/3000 \text{ hours} = .0004160"/1000 \text{ hours}$$

$$t_{iw} = \frac{0.005"}{0.0004160} = 12,000 \text{ hours}$$

$$\hat{M} = 12,000 \text{ hours}$$

$$S = 2,080 \text{ hours}$$

at .90 Confidence Limit

by equation (28)

$$L = \hat{M} - t_{\left(\frac{\alpha}{2}; n-1\right)} \cdot \frac{S}{\sqrt{n}}$$

$$L = 12,000 - \frac{(1.71)(2,080)}{24} = 11,275 \text{ hours}$$

Table V
Material Failure Report Data
VT 12M Piston Rings

DATE	UNIT	ENG. #	HOURS RUN	CAUSE - REASON NOTICED - ACTION	COST (\$)	REPAIR TIME (HOURS)
11/27/56	95306	4	3057	Unknown - faulty ring suspected. Noticed by high oil consumption, starting at 2500 hours. Contributed to liner scoring, and wear of piston land.	500	300
2/28/57	95306	2	2863	Broken top ring	36	500

Table VI
Compression Ring Chance Failure Calculations

A. by (18)

$$\hat{m} = \frac{nt}{r} = \frac{T}{r}$$

$$n = (3)(12)(4)(35) = 5.04(10)^3$$

$$r = 2$$

$$t = 3,000 \text{ hours}$$

$$T = nt = 1.51(10)^7 \text{ hours}$$

$$\hat{m} = \frac{1.51(10)^7}{2} = 7.5(10)^6 \text{ hours}$$

by (17) and (20)

$$L = \frac{2T}{\chi_{\frac{\alpha}{2}; 2r+2}^2} = \frac{3.02(10)^7}{\chi_{.05; 6}^2} = 12.6$$

$$L = 2.04(10)^6 \text{ hours}$$

Table VII

Compression Ring Wear Data

From Cyclic Test Mean and Standard Deviation of Ring Life

VT 12M Engine

1 RING NO.	2 W WEAR $(10)^{-3}$ in	3 W WEAR RATE $(10)^{-3}/(10)^3$ hrs.	4 t_i RING LIFE FROM WEAR (hrs.)	5 $t_i - M$	6 $t_i - M^2$ hrs $(10)^6$
1R	0.5	0.83	21,600	8,400	70.6
2R	1.0	1.67	10,800	2,400	5.8
3R	1.5	2.50	7,200	6,000	36.0
4R	1.0	1.67	10,800	2,400	5.8
5R	0.5	0.83	21,600	8,400	70.6
6R	1.5	2.50	7,200	6,000	36.0
1L	1.0	1.67	10,800	2,400	5.8
2L	1.5	2.50	7,200	6,000	36.0
3L	0.5	0.83	21,600	8,400	70.6
4L	1.0	1.67	10,800	2,400	5.8
5L	0.5	0.83	21,600	8,400	70.6
6L	1.5	2.50	7,200	6,000	36.0
TOTALS			158,400		449.0

Table VIII
Compression Ring Wearout Calculations
Cyclic Load Tests

A. SAMPLE CALCULATIONS

1. WEAR RATE

$$\text{in } (10)^{-3}/(10)^3 \text{ hrs} = \text{Column 3} = \frac{.012 \cdot (10)^3}{5.98(10)^2}$$

$$\frac{[\text{WEAR}(10)^{-3} \text{ in}] \cdot (10)^3}{\text{OP. TIME}} = \frac{.012 \cdot (10)^3}{5.98(10)^2} \text{ hrs.}$$

2. RING LIFE

$$\frac{\text{CLEARANCE}}{\overset{\circ}{W}} = \frac{\delta}{W} = \frac{.018''}{W("/\text{hrs})}$$

B. MEAN AND STANDARD DEVIATION

by equation (25)

$$\hat{M} = \frac{\sum_{i=1}^{12} t_i}{r_{\text{wear}}} = 13,200$$

by equation (26)

$$\hat{\sigma} \equiv s = \sqrt{\frac{\sum_{i=1}^{12} |t_i - \hat{M}|^2}{r_{\text{wear}}}} = 6,100$$

Table IX
Material Failure Report Data
VT 12M Main Bearings

DATE	UNIT	ENG. #	HOURS RUN	CAUSE - REASON NOTICED - ACTION	COST (\$)	REPAIR TIME (hours)
1/11/61	95307	3	1980	Loose bearing cap - low lube oil pressure, revealing wiped bearing.	4500	300
3/6/61	95310	3	2366	Unit reported cause pos- sibly due to: (1) Time in service (2) Increased pressure resulting from recent top overhaul (3) Overload at full power. No prior notice by low lube oil pressure.	2393	525

Table X
Main Bearing Chance Failure Calculations

A. by (17) $\hat{m} = \frac{nt}{r}$

$$n = (7)(4)(35) = 9.8(10)^2$$

$$t = 3,000 \text{ hrs. } T = 2.94(10)^6 \text{ hrs.}$$

$$\hat{m} = 1.46(10)^6 \text{ hrs.}$$

by (20) $L = \frac{2T}{\chi^2_{.05;6}} = 4.66(10)^5 \text{ hours}$

Table XI
Main Bearing Wear Data
From Cyclic Test

1 BEARING NO.	2 W WEAR (598 hrs) (10) ⁻⁴ in	3 W WEAR RATE in/(10) ³ hrs.	4 t _i wearout BEARING LIFE FROM WEAROUT	5 t _i - M hours	6 t _i - M ² hours • (10) ⁶
1	2	3.33	5,100	840	.70
2	2.5	4.17	4,100	1,840	3.38
3	1.5	2.5	6,800	860	.74
4	1.5	2.5	6,800	860	.74
5	2.0	3.33	5,100	840	.70
6	3.0	5.0	3,400	2,540	6.45
7	1.0	1.67	10,200	4,260	18.10
Totals			41,500		30,81

Table XII
Main Bearing Wearout Calculations
Cyclic Endurance Test

A. Sample calculations for Table IV are the same as calculations of Table XII.

B. MEAN AND STANDARD DEVIATION, CYCLIC LOAD TESTS

by equation (25)
$$\hat{M} = \frac{\sum_{i=1}^7 t_{iw}}{r_{wear}} = \frac{41,500}{7} = 5940 \text{ hrs.}$$

by equation (26)
$$S = \sqrt{\frac{\sum_{i=1}^7 (|t_{iw} - M|)^2}{r_{wear}}}$$

$$= \sqrt{\frac{30.81(10)^6}{7}}$$

$$S = 2100 \text{ Hours}$$

Table XIII

Main Bearing Wear Data

From Service Operation

(Operation Time 2005 Hours)

1	2	3	4	5	6
MAIN BEARING NO.	W WEAR (10) ⁻⁴ in.	W WEAR RATE (10) ⁻⁴ in/ (10) ³ hrs	t _i LIFE (hrs)	t _i - M (hours)	t _i - M ² (10) ⁶ (hours)
1	2.0	1.0	20,000	700	.49
2	2.5	1.25	16,000	3,300	10.9
3	2.0	1.0	20,000	700	.49
4	1.5	0.75	26,700	7,400	54.7
5	2.0	1.0	20,000	700	.49
6	2.5	1.25	16,000	3,300	10.9
7	2.5	1.25	16,000	3,300	10.9
TOTALS			134,700		88.87(10) ⁶

Table XIV
Main Bearing Wearout Calculations
From Service Operation

A. Sample calculations for Table XII are the same as calculations of Table XIV.

B. MEAN AND STANDARD DEVIATION, IN-SERVICE

by equation (25)

$$\hat{M} = \frac{\sum_{i=1}^7 t_{iw}}{r_{\text{wear}}} = \frac{134,700}{7}$$

$$\hat{M} = 19,300 \text{ hours}$$

by equation (26)

$$S = \sqrt{\frac{\sum_{i=1}^7 (|t_{iw} - M|)^2}{r_{\text{wear}}}} = \sqrt{\frac{88.87(10)^6}{7}}$$

$$S = 3,560 \text{ hours}$$

Table XV
Material Failure Report Data
Remaining Central Group Components
VT 12M

COMPONENT	DATE	UNIT	ENG. #	HOURS RUN	CAUSE - REASON NOTICED - ACTION	REPAIR	
						COST (\$)	TIME (hrs)
Connecting Rod Bearing	5/5/57	95311		153	Poor or faulty Bearing - yoke of Connecting Rod driven th- rough engine block. Connect- ing Rod bolts subjected to ex- treme tension.	8000	240
Connecting Rod Bearing	6/21/60	95316	1	2925	1 Bearing worn and flaked. No- ticed when bear- ing started turn- ing in the Con- necting Rod. All other connecting rod bearings (4 engines) showed no negligible wear.	--	360
Connecting Rod Bearing	7/11/62	95319	4	--	Bearing turned and overlapped itself. Noticed as engine "froze" from a low idle.	1633	193
Crankshaft	7/4/61	95316	1	361	Fracture at Con Rod Pin location.	400	250

Table XVI

Chance Failure Calculations

VT 12M Remaining Central Group Components

(See Table II for sample calculations)

COMPONENT	n NO. OF COMPONENTS	t HOURS OP.	T HOURS	r NO. FAILURES	m HOURS	L (.90 Con- fidence) HOURS
Connecting Rod	(12)(4)(35)	3000	$5.04(10)^6$	0	--	$1.68(10)^6$
Piston Pin	(12)(4)(35)	3000	$5.04(10)^6$	0	--	$1.68(10)^6$
Engine Block	(12)(4)(35)	3000	$5.04(10)^6$	0	--	$1.68(10)^6$
Connecting Rod Bushing	(12)(4)(35)	3000	$5.04(10)^6$	0	--	$1.68(10)^6$
Connecting Rod Bearing	(12)(4)(35)	3000	$5.04(10)^6$	3	$1.68(10)^6$	$0.65(10)^6$
Crankshaft	(12)(4)(35)	3000	$5.04(10)^6$	1	$5.04(10)^6$	$1.06(10)^6$

APPENDIX F

Load Schedule, Cyclic Endurance Test
8-Hr Test Cycle, 42 Cycles
for 600 Hours Total Engine Time

Conducted By
U.S. Navy Marine Engineering Laboratory
Annapolis, Md.

Run No.	Power Output		Clutch Position	Duration	
	Rated Load and Speed, %	Load and Speed		Hr	Min
1	Rated load at rated speed	600 bhp at 2100 rpm	Forward	2	00
2	85% rated load at rated speed	510 bhp at 2100 rpm	Forward	1	00
3		Idle	Neutral	0	10
4	Rated load at rated speed	600 bhp at 2100 rpm	Forward	1	50
5		Idle	Neutral	0	10
6	85% rated load at rated speed	510 bhp at 2100 rpm	Reverse	0	30
7		Idle	Neutral	0	10
8	110% load at rated speed	660 bhp at 2100 rpm	Forward	2	00
9	Shutdown			0	10
		Total		8	00

Note: The engine was operated for a total of forty-two 8 hour cycles.

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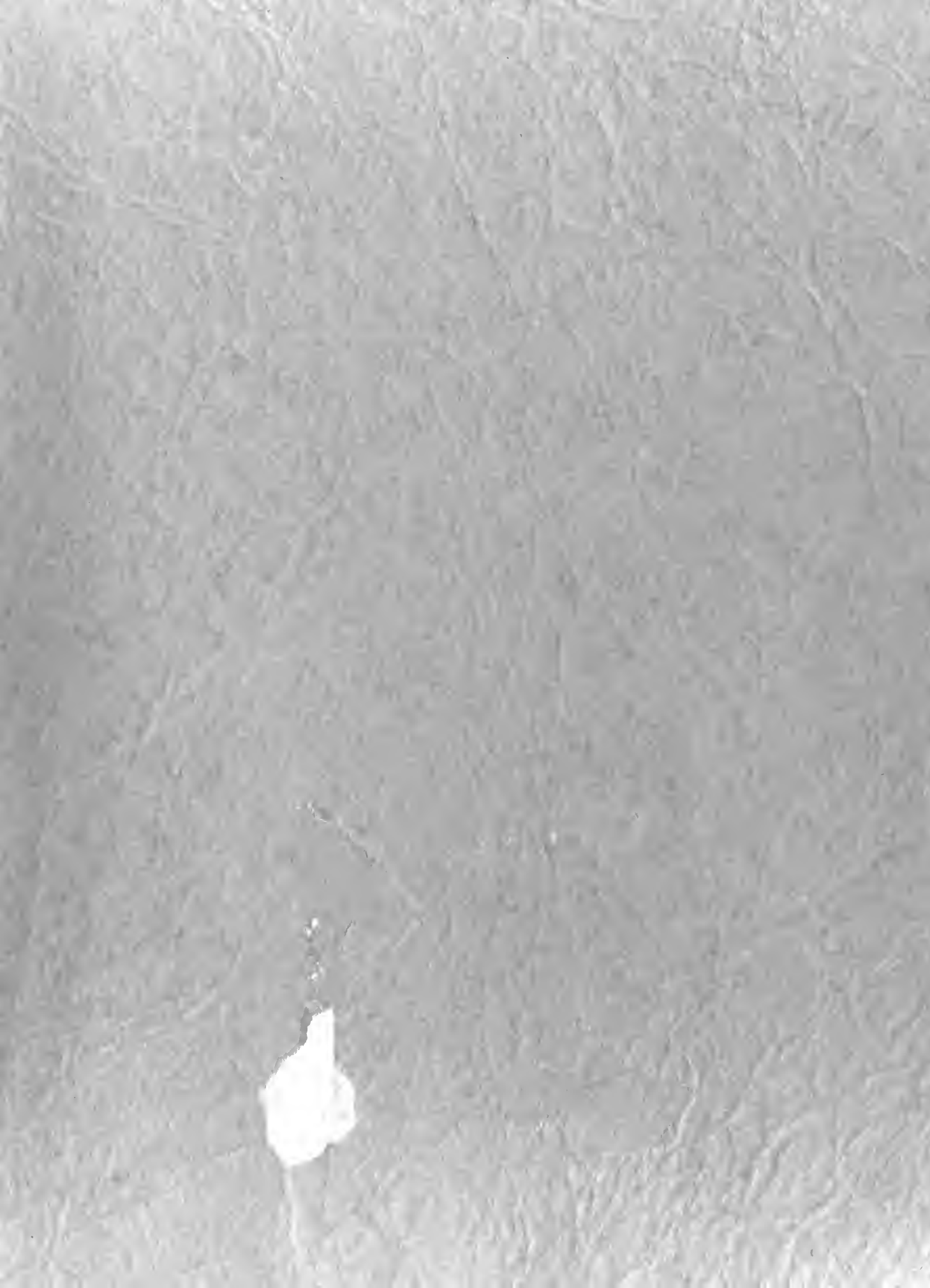
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